Coal Mining in America: An Explanation of the Decline and Disappearance of the Union Safety Premium

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Abstract

In 2000, the safety records of union underground bituminous coal mines outperformed nonunion mines consistently and statistically significantly. By 2015, this union safety premium had entirely disappeared and has remained nonexistent. At the same time, steep declines in the demand for coal resulted in a compositional change among these mines toward ones that were in continuous operation for longer periods of time. This paper makes sense of how these new facts might be related and depend on each other. A model of firm and worker safety investment decisions is introduced to explain differences in safety outcomes across firms of varying operation lifetimes. Using both 2SLS and a control function approach to correct for the endogeneity of mine operation lifetime and firm safety investments, several causal relationships suggested by the model are estimated using mine-level underground bituminous coal mine data from 2000-2022. There is evidence that mine safety investments cause a reduction in injury incidence and that longer operation lifetimes cause mines to increase safety investments. At the same time, worker safety investment appears to decline as operation lifetimes increase. This paper presents evidence to support a simple story where longer operation lifetimes cause mines to have better safety outcomes, and a compositional change in nonunion mines toward those with longer operation lifetimes begets the disappearance of the union safety premium.

1 Introduction

Coal mine unions have long preoccupied researchers who study the relationship between organized labor and workplace safety. Historically, the literature around unions and workplace safety has reflected debate rather than consensus. For every paper measuring safety benefits of unionization (e.g., Gillen, Baltz, Gassel, Kirsch, and Vaccaro (2002); Boal (2009)), there is one readily available that concludes that union safety effects are ambiguous (e.g., Li, Rohlin, and Singleton (2022)) — or even negative (e.g., Appleton and Baker (1984), Reardon (1996)). Morantz (2013), a relatively recent and well-cited addition to the literature,[1] might seem to be the final word on whether unions make a difference when it comes to coal mine safety. Using detailed, mine-level data, Morantz (2013) presents robust estimates that suggest unionization predicts a 14 to 32 percent drop in traumatic injuries from 1993-2010. More recent data call into question the stability of these estimates, however, and indicate that this union safety premium no longer exists.

In this paper, I update the results of Morantz (2013) by estimating trends in the union safety premium with 12 additional years of data. To explain these trends, I hypothesize a

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[1]Google Scholar reports 128 citations as of October 4, 2024.

narrative based on economic theory that is consistent with estimates of the union safety premium and other coincident trends. For the empirical parts of this paper, I create a panel dataset of 1,650 underground bituminous coal mines from 2000-2022 with data that I gather from the EIA (U.S. Energy Information Administration), MSHA (Mine Safety and Health Administration), and S&P Capital IQ.

Using these data, I first establish some facts. First, as I have already alluded to, the union safety premium documented by Morantz (2013) declined and disappeared. To clarify definitions, the "union safety premium" is simply the average amount by which union mines outperform nonunion mines' safety records, particularly with respect to rates of traumatic injuries.[2] Second, domestic coal consumption and production in the United States peaked from 2005-2010 and have since been in steep and persistent decline through the present day. Third, declining coal consumption and production coincided with the exit of underground mines such that a meaningful proportion of production shifted to mines with longer operation lifetimes. Crucially, while an overall union safety premium is indeed identifiable and statistically significant at the beginning of the sample period, a stable union safety premium never exists from 2000-2022 when restricting attention to mines with the longest observed operation lifetimes. The first and third facts are novel contributions of this paper.

To make use of the patterns in the data and explain how these facts might be related and depend on each other, I construct a model of firm and worker safety investment decisions with firms of varying operation lifetimes. This model of safety dynamics features a representative worker and a representative firm that operates for either one or two periods, where the second period occurs with some probability that is known to both the firm and worker. Both firms and workers face exogenously given accident costs but can influence the probability of an accident with safety investments. In the first period, firms make a one-time safety investment. Workers can similarly engage in "self-protection" (Ehrlich and Becker (1972)), which is akin to choosing a constant safety investment level that they must sustain through the first and, should it occur, second periods. Safety production (i.e., reduction in accident probability) thus depends on firm- and worker-level safety investments, which in turn both depend on the probability that the firm remains in operation though the second period.

In the model, employees act as intermediaries between firm-level workplace safety investments and actual safety outcomes. Analysis of this process is key because, when firms invest in workplace safety improvements, it does not necessarily follow that the workplace becomes safer. Returns to firm safety investments depend critically on the pervasiveness of moral hazard among employees and the extent to which there is an analogue of the "Peltzman Effect" (Peltzman (1975)). One consequence of this is that workers always face a tradeoff between increasing their own safety investment and reducing expected accident costs via reductions in accident probability, but, under extreme conditions, firms may not. That is, if workers sufficiently cut back their own safety expenditures when firms make a

[2]Morantz (2013) implicitly uses the same definition when discussing "union safety effects." See Section 2 for a full definition of traumatic injuries.

safety investment, firms can make no investment in safety at all and simultaneously minimize expected accident costs.

I use this model to motivate and guide several empirical analyses of the coal mines in my sample. The model suggests three theoretically ambiguous and testable relationships between firm and worker safety investment and firm operation lifetime. First is the effect of firm safety investment on workplace injuries; second, the effect of firm operation lifetime on firm safety investments; and, third, the effect of firm operation lifetime on worker safety investments and effort. The latter two relationships are derived directly from the first-order conditions of the firm's and worker's problems. By estimating the direction of these effects I can infer the relative magnitude of moral hazard induced by firm safety investment.

Estimates of the effects of mine operation lifetime and safety investments are highly susceptible to endogeneity bias. To identify the direction of the relationships implied by the model and assess causality, I use instrumental variables designs with both a control function approach (for count outcomes and continuous endogenous explanatory variables, as recommended by Wooldridge (2015)) and standard two-stage least squares (when both outcome and endogenous explanatory variables are continuous). I use three types of instruments for mine-level variables. The first exploits geological variation in coal seam height across mines; the second treats regional variation as an exogenous shifter of mine-level variables; and the third uses lagged values. Estimates are generally directionally consistent regardless of what instruments are used but vary in magnitude. For estimates of the union safety premium, I replicate the negative binomial specification of Morantz (2013), which relies exclusively on selection on observables for identification.[3]

The empirical results suggest that mine safety investments cause injuries to fall and that increases in mine operation lifetime cause mine safety investments to increase. These results are not fully robust to specification, but the specifications I report that produce contradictory estimates have both weak instrument problems and numerous potential exclusion restriction violations. One explanation for the potential inconsistency of the results is that worker and firm safety investment levels move in opposite directions with respect to mine operation lifetime.

Interpreted in the context of the model and the industry-wide trends I document, these empirical results offer a partial explanation to the question that drives this paper: *What happened to the union safety premium?* In short, this paper presents evidence to support a simple story where longer operation lifetimes cause mines to have better safety outcomes, and a compositional change in nonunion mines from around 2012-2022 toward those with longer operation lifetimes begets the disappearance of the union safety premium.

Decisions affecting workplace safety are broadly relevant across multiple fields of economics and social science, and this paper contributes to several literatures. Most obvious

[3]Note that the *causal* effect of unions on workplace safety outcomes is actually outside the scope of this paper. Union effects are distinct from the union safety premium, which is simply the difference in average outcomes across union and nonunion mines. (This is partially why I depart from Morantz (2013) and use the term "union safety premium" instead of "union safety effect.") This mitigates legitimate concerns about omitted-variable bias polluting estimates of union effects.

are connections with labor questions such as those related to unions and compensating wage differentials (Freeman and Medoff (1984); Morantz (2009); Morantz (2013); Guardado and Ziebarth (2019)). Firms can choose safety input levels and compete to offer working conditions that are favorable to workers. But they may also face conflicting incentives to invest in safety from competitive pressures generated by product and labor markets, thus making workplace safety relevant to industrial organization (Marette (2007); McManus and Schaur (2016); Chang and Jo (2019); Posner (2021)). Coal mining is a highly regulated industry, and there are potentially important policy implications for regulation formation and accident reporting practices (H. B. Christensen, Floyd, Liu, and Maffett (2017); Morantz (2017)). The study of workplace accidents resulting in injury naturally intersects with health research and health economics (Cummins and Olson (1974); Baidwan et al. (2018)) — although detailed analysis of these relationships is left for future work — and workers may make human capital investments via "self-insurance" or "self-protection" when facing substandard working conditions (Ehrlich and Becker (1972)). Workers may also engage in learning by doing with respect to best safety practices, thereby affecting the accumulation of firm-wide knowledge about safety and raising questions about the relative importance of firm systems and worker behavior (Levitt, List, and Syverson (2013)).

The rest of this paper proceeds as follows. Section 2 describes key, motivating empirical facts, the underground bituminous coal mine empirical setting, and the data used in this paper. Section 3 introduces the model of firm and worker safety investment decisions. Section 4 presents the paper's empirical analyses. Section 5 concludes.

2 Empirical setting and data

2.1 Motivating empirical facts

In the first decade of the 21st century, consumption and production of coal in the United States reached their highest levels ever.[4] Demand has since declined steadily, largely due to cheaper natural gas and renewable substitutes (Johnsen, LaRiviere, and Wolff (2019); Watson, Lange, and Linn (2023); Gruenspecht (2019)). By 2022, the domestic coal market was less than half of its 1.5 billion short ton peak of 15 years prior (see Figure 1, Panel A). Despite presidential campaign promises to "bring back coal,"[5] the economic reality of cheaper substitutes, coupled more recently with billions of federal dollars flowing into green energy technologies and natural gas projects,[6] has made a fantasy of the idea that there will be a rebound in coal demand.[7] This trend is made all the more difficult to reverse

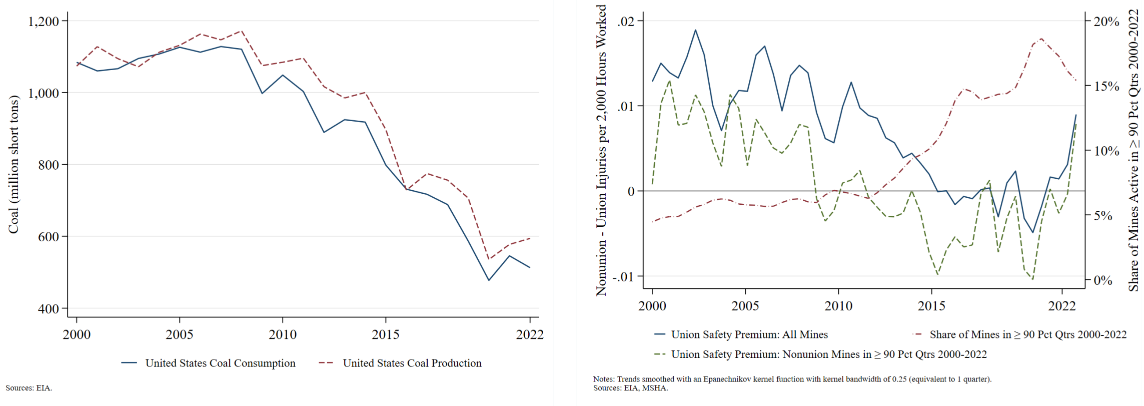
[4] U.S. Energy Information Administration, *Coal explained: Use of coal*, https://www.eia.gov/energyexplained/coal/use-of-coal.php (accessed August 20, 2024).

[5] Di Giacomo, Nagl, Steinbrunner, et al. (2022) find a positive effect of coal production on the Republican vote share in the 2016 election.

[6] See, e.g., USDA Press, "Biden-Harris Administration Announces $7.3 Billion in Clean Energy Investments from the Investing in America Agenda, Largest Investment in Rural Electrification Since the New Deal," *U.S. Department of Agriculture*, September 5, 2024; Max Bearak, "It's Not Just Willow: Oil and Gas Projects Are Back in a Big Way," *The New York Times*, April 6, 2023.

[7] While domestic coal usage has fallen, global coal consumption has not as developing nations use it to fuel their economic growth. In particular, demand for coal has remained persistently high over the last decade in

by a slew of completed, planned, and predicted coal-fired power plant retirements (Fell and Kaffine (2018); Davis, Holladay, and Sims (2022)). In 2019, even Cecil Roberts, the president of the UMWA (United Mine Workers of America) coal miner union, conceded, "Coal is not back. Nobody saved the coal industry."[8]



(a) Coal Consumption and Production

(b) Underground Bituminous Coal Mines

Figure 1: 21st Century United States Coal Mining Trends

Coincident with this demand shock were marked changes in workplace safety outcomes across underground bituminous coal mines, which accounted for between 30 and 38 percent of coal production from 2000-2022.[9] Figure 1, Panel B illustrates new facts about these mines from 2000-2022 that I use to motivate this paper.

Two versions of the union safety premium are plotted on the left-hand y-axis of Figure 1, Panel B. Specifically, the union safety premium trends shown in the figure are differences in the annual rates of traumatic injuries per FTE (full-time equivalent, i.e., 2,000 hours) between nonunion and union underground bituminous coal mines. Recall that the union safety premium is the average amount by which union mines outperform nonunion mines' safety records. This means that a positive union safety premium (above the bold,

China and India. See, e.g., Bloomberg News, "Coal Use Seen Peaking next Year as India, China Determine Future," *Bloomberg*, March 20, 2023; Paolo Agnolucci, Peter Nagle, and Kaltrina Temaj, "Declining coal prices reflect a reshaping of global energy trade," *World Bank Blogs*, March 21, 2023.

[8]Cecil Roberts, "Cecil Roberts: Shutting down coal will not solve climate change (Opinion)," *Charleston Gazette-Mail*, October 2, 2019.

[9]I focus on underground bituminous coal mines in this paper, in keeping with Morantz (2013), for the relative homogeneity of both their work environments and the demand for their output. There are four main "ranks" of coal, listed here in decreasing order of carbon content: anthracite, bituminous, subbituminous, and lignite. Bituminous coal is used largely for electricity generation, but it is also an input in coking coal for iron and steel production. U.S. Energy Information Administration, *Coal explained*, https://www.eia.gov/energyexplained/coal/ (accessed October 6, 2024). In general, coal is used almost exclusively for electricity generation; 91.7 percent of coal consumed in the United States during 2022 went toward electric power. U.S. Energy Information Administration, *Coal explained: Use of coal*, https://www.eia.gov/energyexplained/coal/use-of-coal.php (accessed August 20, 2024). Historically, nearly all coal was extracted from mines where miners worked underground, but innovations in strip mining and mountaintop removal techniques have shifted production of coal toward surface mines. Notably, 40 percent of all United States coal production during 2021 was in Wyoming, which extracts coal from the Powder River Basin, and approximately 25 percent of the coal extracted in the state came from a single surface mine. Wyoming State Geological Survey, *Coal Production & Mining*, https://www.wsgs.wyo.gov/energy/coalproduction-mining.aspx (accessed April 11, 2023).

horizontal line at 0) implies union workplaces are safer than nonunion workplaces; a negative union safety premium (below the horizontal line) implies nonunion workplaces offer a safety advantage. The solid blue line in Figure 1, Panel B shows the overall union safety premium, and the dashed green line shows the union safety premium when nonunion mines are restricted to only those with the longest operation lifetimes in the sample, defined as positive coal production in at least 90 percent of quarters from 2000-2022.[10]

There are two key takeaways from Figure 1, Panel B regarding trends in the union safety premium. First, the overall union safety premium shows some volatility from 2000-2010, but is generally stable and always manifestly positive. Around 2010, it begins to decline, until it disappears entirely by 2015. Second, nonunion mines with the longest operation lifetimes in the 21st century are not consistently less safe than union mines from 2000-2010, and there is no union safety premium for these mines from 2010-2022. There is a return to positive territory for both union safety premiums at the very end of 2022, but data are not available for more recent quarters to see whether this is simply volatility of the sort observed earlier in the sample or a nascent trend.

The dashed red line plotted on the right-hand y-axis of Figure 1, Panel B shows a compositional change among underground bituminous coal mines with respect to operation lifetime. From 2000-2022 the share of underground bituminous coal mines active for at least 90 percent of the sample period quadrupled. This is a mechanical consequence of mine exit that occurred as a result of diminished demand for coal. As the number of mines dwindles over time, those mines that remain in operation for the duration of the observation period will necessarily make up a larger share of mines at the end of the period than the beginning.

The fact that a stable union safety premium never appears to exist for mines with the longest operation lifetimes and that the overall union safety premium begins to decline at the same time the composition of mines changes toward those with the longest operation lifetimes might suggest a few theories. Perhaps poor safety practices lead mines to rack up fines so significant that it remains unprofitable to continue operation. But Jordan, Lange, and Linn (2018) find that rising production costs explain about two-thirds of coal mine closures from 2002-2012, with natural gas prices and reduced electricity consumption explaining most of the rest.

It could be the case that productivity and safety are complementary or that "good managers" lead mines that are both more productive (with reduced closure probability) and safer. But, as discussed at greater length in Section 4, geological features of mines — specifically coal seam height — strongly predict the number of quarters a mine is active from 2000-2022. This is consistent with the conclusions of Jordan et al. (2018): it is more difficult to extract coal when the coal seam is small, and this raises production costs and reduces profitability. Thus, it seems that managerial quality can have, at best, marginal

[10] As discussed in Section 4, the story is the same regardless of whether the union safety premium is calculated using nonunion mines with longer operation lifetimes compared to all union mines or both union and nonunion mines with longer operation lifetimes. Additionally, the results are not sensitive to threshold for operation lifetime — 90 percent here — that is used.

influence on mine productivity and closure probability.[11]

Expectations about mine operation lifetime itself might affect the safety decisions of both mines and miners. It is the validity of this line of reasoning that I probe in this paper.

2.2 Mining injuries, mining unions, and accident costs

While the economics of workplace safety are relevant to all jobs,[12] the coal mining industry in particular provides a superb setting to study the causes and consequences of variation in firm-level workplace safety. Underground coal mines are dark, dirty, and dangerous workplaces. The Fatality Reports prepared by MSHA are morbid fascinations in graphic detail that cover the myriad ways miners have perished on the job: crashed, crushed, dismembered, drowned, electrocuted, exploded, fallen, severed, slipped, suffocated, twisted, and on and on.[13] Yet, while underground mining machine operators still boast a fatality rate more than five times the United States civilian occupation national average,[14] mining coal has become a substantially safer occupation over the last 100 years (see Figure 2).

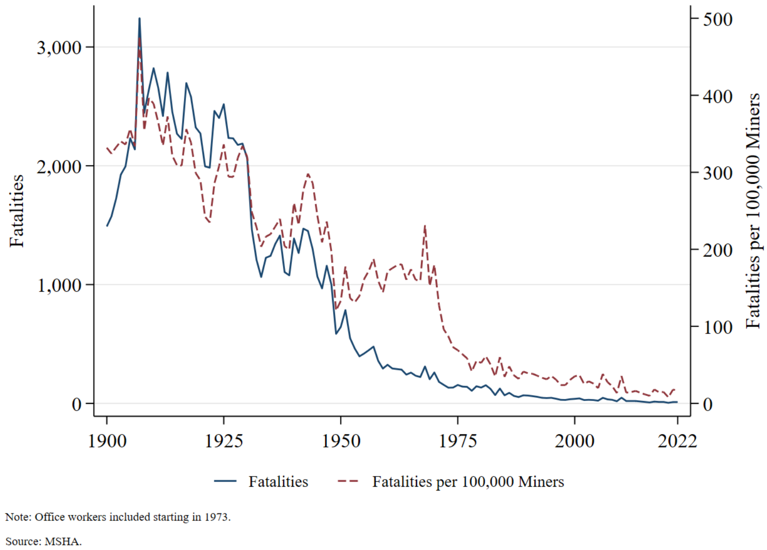


Figure 2: United States Coal Mining Fatalities: 1900-2022

These dramatic gains in safety outcomes can be variously attributed to technological progress, competitive pressures, labor organization efforts, and government regulation.[15] Breslin (2010) provides an exhaustive history of federal mining safety and health

[11] Appendix F contains a brief summary of the relationship between safety and productivity in the data.

[12] Even the most sedentary corporate foot soldier may trade off the neck and back health promoted by expensive ergonomic sophistication with low-cost, uncomfortable workstation configurations.

[13] Mine Safety and Health Administration, *Fatality Reports*, https://www.msha.gov/data-andreports/fatality-reports/search (accessed April 8, 2023).

[14] U.S. Bureau of Labor Statistics, *Civilian occupations with high fatal work injury rates*, https://www.bls.gov/charts/census-of-fatal-occupational-injuries/civilian-occupations-with-high-fatal-work-injury-rates.htm (accessed August 19, 2024).

[15] See, e.g., Mine Safety and Health Administration, *Injury Trends in Mining*, https://arlweb.msha.gov/mshainfo/factsheets/mshafct2.htm (accessed October 7, 2024).

research and explains how most mine safety legislation was passed after lobbying by miners' unions or in response to deadly accidents.

Rates of unionization have been in secular decline across the entire United States economy since the 1980s, and coal mining is no exception. According to the Bureau of Labor Statistics, "The 2022 unionization rate (10.1 percent) is the lowest on record."[16] In the 1940s, 90 percent of coal miners in the United States belonged TO a union (K. Christensen (2014)). In the 1980s, 60 percent of coal miners were unionized,[17] and only 10 percent of mine-quarters from 2000-2022 are associated with a unionized mine in the sample this paper uses (see Table 1).

Morantz (2013) hypothesizes that injury reporting practices differ substantially between union and nonunion mines.[18] To overcome this reporting bias, I employ her definition of "traumatic" injuries, which are unlikely to differ in reporting frequency based on a mine's union status. Traumatic injuries are defined to include the following: amputations; enucleations; fractures; chips; dislocations; foreign bodies in eyes; cuts and lacerations; punctures; burns/scalds; crushings; chemical, electrical, and laser burns; and fatalities. I use traumatic injuries as my metric for "real" safety outcomes throughout this paper.

Regardless of union status, mine owners face incentives to minimize accidents. Accidents and worker injuries can impose various costs on mines. In addition to direct costs of accidents (e.g., compensation and settlements to workers, damage to equipment, and fines), mines face indirect costs (e.g., lower miner morale, administrative costs, and opportunity costs incurred by attention spent conducting accident investigations).[19]

2.3 Safety inspections and safety investments

Federal mine oversight took on its modern form in 1977 with the passage of the Federal Mine Safety and Health Act (Mine Act), which created MSHA and required four annual inspections at all underground mines. MSHA develops and enforces safety and health rules for every single mine in the United States.[20]

In addition to the four mandatory inspections required by law, MSHA inspectors conduct additional inspections if high levels of explosive gasses are present at mines and in response to specific complaints.[21] Penalties are assessed against mine operators for noncompliance with regulations, with penalty sizes determined by history of violations, size

[16]"Union membership rate fell by 0.2 percentage point to 10.1 percent in 2022," *U.S. Bureau of Labor Statistics*, January 24, 2023.

[17]Lawrence Mishel, Lynn Rhinehart, and Lane Windham, "Explaining the erosion of private-sector unions," *Economic Policy Institute*, November 18, 2020.

[18]Donado (2015) provides further analysis of this issue. In addition to reporting practices, recording practices may also introduce measurement error. See Thomas S. Tedone, "Counting injuries and illnesses in the workplace: an international review," *Monthly Labor Review, U.S. Bureau of Labor Statistics*, September 2017.

[19]U.S. Department of Health & Human Services, *Safety Pays in Mining: Technical Guide*, https://www.cdc.gov/niosh/mining/content/economics/safetypayscostesttechguide.html (accessed October 7, 2024).

[20]Mine Safety and Health Administration, *Mission*, https://www.msha.gov/about/mission (accessed April 14, 2023).

[21]Mine Safety and Health Administration, *Mine Inspections*, https://www.msha.gov/complianceandenforcement/ mine-inspections (accessed April 14, 2023).

of the business, negligence, seriousness of the offense, and degree of good faith from the operator in correcting the violation promptly.[22] Penalties can be appealed.

During an inspection, MSHA inspectors may determine that a particular regulatory violation is an S&S ("significant and substantial") violation. For this to be the case, four elements must be proven:

1. The underlying violation of a mandatory standard

2. The existence of a discrete safety hazard contributed to by the violation

3. A reasonable likelihood that the hazard contributed to will result in an injury

4. A reasonable likelihood that the injury in question will be of a reasonably serious nature[23]

In other words, S&S violations indicate the absence of materially important safety investments.[24] Actual mine-level investments in workplace safety are not observable, so I assume a mine's frequency of S&S violations is inversely correlated with the mine's safety investments in a meaningful way.

2.4 Data sources

I rely primarily on publicly available data downloaded from MSHA's Mine Data Retrieval System.[25] The database includes quarterly data on mine production and employment reported by mine operators for each coal mine in the United States from 2000 up to the most recent quarter. Each mine accident over the same time period is reported with details on the type and severity of injury, when it happened, and at which mine it occurred. Every mine violation recorded by an MSHA inspector is similarly reported with the date the violation occurred, the violation's severity, and the associated regulation that the mine was not in compliance with. The ownership and management history of each mine is indicated by a mine's "controller" and "operator" history.[26] Information on the location of the mine, what type of coal it extracts, and whether it is an underground operation is also published. Individual files containing these data can be linked by unique MSHA mine identifiers and aggregated to the quarter level. I build a panel dataset of all underground bituminous coal mines in the United States at the quarterly level from 2000-2022.

[22] Mine Safety and Health Administration, *Penalty Assessments and Payments*, https://www.msha.gov/compliance-and-enforcement/penalty-assessments-and-payments (accessed April 14, 2023).

[23] These four elements are written exactly as they appear on the MSHA website. Mine Safety and Health Administration, *Compliance & Enforcement FAQs*, https://www.msha.gov/compliance-enforcement/contesting-citations/compliance-enforcement-faqs (accessed April 14, 2023).

[24] A little under a third of total MSHA violations are S&S violations in the sample I use.

[25] Mine Safety and Health Administration, *Mine Data Retrieval System*, https://www.msha.gov/data-and-reports/mine-data-retrieval-system (accessed July 15, 2024).

[26] The operator can either be a subsidiary of the controller or a third party brought in to manage mine operations. NPR Staff, "Delinquent Mines: About The Data," *NPR*, November 12, 2014.

I supplement the MSHA data with coal mine data collected via the EIA's Form EIA-7A, the "Annual Survey of Coal Production and Preparation."[27] This provides a variable indicating whether a given mine (which is identified by its unique MSHA mine identifier) was unionized for each year from 1983 to 2022. I link this to my panel of MSHA data. Following Morantz (2013), I assume all quarters in a given year have the same union status. The union organization is not always clearly specified, but the UMWA is by far the largest union representing unionized miners.[28] In addition to not having union data at the quarterly level, these data are limited by not including details of strikes and collective bargaining agreements.

I rely on S&P Capital IQ for data on mines' coal seam height at quarterly intervals from 2000-2022. This field is populated for about 80 percent of mine-quarter observations I use for analysis.

In addition to Morantz (2013), I follow guidance for similar data provided by H. B. Christensen et al. (2017) for data cleaning steps and trimming outlier observations in analysis.

2.5 Data summary

After combining data from MSHA, EIA, and Capital IQ, I end up with a mine-quarter panel of 1,650 underground bituminous coal mines from 2000-2022.

These mines are distributed across 34 MSHA offices and 11 MSHA mine districts. As shown in Figure A1, which color codes mines by MSHA office (Panel A) and MSHA mine district (Panel B), the majority of mines are in Kentucky, Illinois, Indiana, Pennsylvania, and West Virginia.[29]

Table 1 shows mine characteristics of interest, summarized at the mine-quarter level, that are used in the empirical analyses in this paper.

[27] U.S. Energy Information Administration, *COAL: DATA*, https://www.eia.gov/coal/data.php (accessed July 15, 2024).

[28] The EIA data indicate that 6 mines in the sample were unionized in 2011 and in 2013 but not in 2012. The total absence of news coverage related to these mines' union status during this time period suggests that this is a data error, so I impute union status for these mines. The MSHA mine identifiers for these mines are 100851, 4200121, 4601537, 4601816, 4606618, and 4609152.

[29] Variation within these geographic units is exploited as an exogenous shifter of mine-level variables in instrumental variables designs employed later in this paper. The reasoning and limitations of this approach are more fully developed alongside its implementation in Section 4.

Table 1: Underground Bituminous Coal Mine Characteristics

	N	Mean	Std. Dev.	Minimum	Maximum
Year	33,653	2,008.59	6.00	2,000.00	2,022.00
Quarter	33,653	2.49	1.12	1.00	4.00
Union	33,653	0.10	0.30	0.00	1.00
Mine Age	33,653	12.41	11.64	0.00	52.00
Mine Size (100 FTEs)	33,653	1.01	1.41	0.00	14.30
Controller Size (100 FTEs)	33,653	11.27	17.32	0.00	89.28
Coal Production (short tons)	33,653	217,847.36	419,393.91	1.00	3,882,241.00
Underground Labor Hours	33,653	50,340.95	70,447.75	5.00	714,766.00
Productivity (tons/2,000 hrs)	33,653	7,216.35	5,639.64	0.58	61,803.61
Penalty Pts Last 4 Qtrs	33,653	6.30	9.93	0.00	123.25
Total Injury Count	33,653	2.53	4.11	0.00	70.00
Traumatic Injury Count	33,653	0.84	1.53	0.00	29.00
Total MSHA Violation Count	33,653	27.84	36.16	0.00	438.00
S&S MSHA Violation Count	33,653	8.16	12.17	0.00	271.00
Mines with Same MSHA Office in Qtr	33,653	28.72	28.33	1.00	121.00
Mines in MSHA District in Qtr	33,653	68.36	48.11	1.00	187.00
Coal Seam Height (inches)	27,224	59.67	24.47	1.00	780.00

Appendix A contains additional figures that summarize trends and distributions of key variables in the data.

3 Model

The model introduced here modifies one employed by Guardado and Ziebarth (2019) (which is itself based on Ehrlich and Becker (1972)) that is used to study compensating wage differentials. As with Guardado and Ziebarth (2019), I assume workplace accident risk is endogenously determined by worker safety inputs, but my modifications allow firm safety investments to simultaneously vary. I consider a scenario in which workers are employed by a firm that exists for one or two periods.

The objective of the model is to study how the interaction of worker and firm safety investments varies depending on the probability of firm closure. Using the model, I show that the direction and magnitude of the following three relationships are theoretically ambiguous at the firm level:

1. The change in the probability of an accident or injury in response to a safety investment by the firm.

2. The change in safety investment levels *by the firm* in response to a change in the expected operation lifetime of the firm.

3. The change in safety investment levels *by workers* at the firm in response to a change in the expected operation lifetime of the firm.

To derive these results — which correspond to the three propositions put forth in this section — I use a relatively parsimonious model that imagines a simplified world of representative agents for both a firm in a homogeneous industry and a worker at the firm. The first period always occurs, and there is a probability δ, known to both the firm and the worker, that the second period occurs ($0 < \delta < 1$).[30] That is, the firm shuts down after the first period with probability $1 - \delta$. There is a probability p that a workplace accident occurs ($0 < p < 1$). Workers can lower risk p via safety inputs e, which depend on firm safety investments S. The safety production function is thus $p(e(S), S)$, with $\frac{\partial p}{\partial e} < 0, \frac{\partial^2 p}{\partial e^2} > 0$ and $\frac{\partial p}{\partial S} < 0, \frac{\partial^2 p}{\partial S^2} > 0$. Note that these relationships pertain to *partial effects*. Under the framework of this model, we have the following proposition regarding the *total effect* of firm safety investments on accident probability.

Proposition 1 *The total effect of firm safety investments on accident probability* $\left(\text{i.e.,} \frac{dp}{dS}\right)$ *is theoretically ambiguous.*

The reasoning that underlies this proposition is straightforward. Using the chain rule, the total effect of S on p can be represented by:

$$\frac{dp(e(S), S)}{dS} = \underbrace{\frac{\partial p}{\partial e}}_{<0} \cdot \underbrace{\frac{\partial e}{\partial S}}_{\text{ambiguous}} + \underbrace{\frac{\partial p}{\partial S}}_{<0} \tag{1}$$

This decomposes the total effect of firm safety investments into a direct effect of workplace safety investments on real safety outcomes and an indirect effect whereby workers convert firm safety investments into real safety outcomes by, for example, adjusting conscientiousness and competently using new safety equipment.

The sign and magnitude of $\frac{\partial e}{\partial S}$ in (1) depends primarily on how workers adjust risky behavior in response to changes in workplace safety infrastructure. If $\frac{\partial e}{\partial S} > 0$, there are synergies between workers' decisions to create safety inputs and firm safety investments. Situations where $\frac{\partial e}{\partial S} < 0$ arise when workers cut back on the intensity of their safety efforts in response to an improvement the firm makes to the workplace safety environment. When $\frac{\partial e}{\partial S} < 0$ such that $\left|\frac{\partial p}{\partial e} \cdot \frac{\partial e}{\partial S}\right| > \left|\frac{\partial p}{\partial S}\right|$, real safety outcomes worsen in response to firm safety investments. This latter scenario is analogous to the canonical case, illuminated by Peltzman (1975), of drivers responding to enhanced safety features in automobiles by driving more recklessly and causing more accidents, thereby offsetting in aggregate the effect these safety enhancements have in reducing individual accident cost and severity.[31]

[30] In the underground bituminous coal setting of this paper, the height of a mine's coal seam strongly predicts operation lifetime. This is shown in Figure 4, Panel B and discussed in greater depth throughout Section 4. The height of a mine's coal seam — a good proxy for the amount of coal available to extract — should be understood by those working in close proximity to it daily. Thus, both workers and management could be reasonably expected to have a well-informed approximation of their mine's remaining operation lifetime.

[31] Here I assume that safety investments by the firm do not affect A. This assumption is well-suited to the coal mining setting I consider in the empirical sections of this paper. For example, a mining company may invest in structural supports that reinforce the stability of mine walls. These could reduce the probability of mine collapse, but, should the mine collapse, the damage caused by the accident would be the same regardless of safety investment. This admittedly puts aside damages the firm might owe resulting from post-accident litigation; these damages might be mitigated if the firm could demonstrate that it made proactive safety investments prior to an accident. Still, the mine setting could conceivably have A invariant to changes in S, in contrast to an automobile setting, where, for example, airbags and seat belts generally reduce the cost of

3.1 Firm safety investment

Factor and output markets are assumed to be perfectly competitive, such that the firm is a price taker for safety technology and resources. For simplicity, and to focus on the workplace safety questions at hand, costs of all production factors are normalized to one as well as the price of a homogeneous output. The firm discounts future profits at a rate β ($0 < \beta < 1$). In the first period, the firm makes a decision about a safety investment S, as well as an output Q to produce in both periods ($S, Q > 0$). In the event of an accident, the firm incurs a cost A. This gives us the firm's profit function:

$$\pi = Q - S - p(e(S), S)A + \beta \cdot \delta \cdot [Q - p(e(S), S)A] \tag{2}$$

Assuming perfect competition, $\pi = 0$.[32] Additionally, we know that Q is some function of S. Consider the case of a saw mill making a safety investment. The mill could invest in safety guards for blades that enable workers to get closer to their work and make fewer mistakes, thereby increasing output $\left(\frac{\partial Q}{\partial S} > 0\right)$. Or, the mill could invest in an automatic saw shutdown mechanism that, while it might save a finger, destroys the blade more frequently and decreases output overall $\left(\frac{\partial Q}{\partial S} < 0\right)$.[33] This leaves us to obtain the following relationship after taking the total derivative of (2) with respect to δ:[34]

$$\frac{\partial S}{\partial \delta}\left[1 + \left(\frac{dp}{dS}A - \frac{\partial Q}{\partial S}\right)(1 + \beta\delta)\right] = \beta[Q - pA] > 0 \tag{3}$$

The fact that $\beta[Q - pA] > 0$ is a consequence of the zero-profit condition and $S > 0$. To demonstrate this, assume for the sake of contradiction that $\beta[Q - pA] \leq 0$. If $\beta[Q - pA] = 0$, then for $\pi = 0$ to hold it must be the case that $S = 0$. If $\beta[Q - pA] < 0$, then for $S > 0$ to hold it must be the case that $\pi < 0$. This completes the proof.

Proposition 2 *The sign of $\frac{\partial S}{\partial \delta}$ is theoretically ambiguous. Due to the zero-profit constraint, it cannot be the case that firm safety investment is increasing in the probability of a second period for large, positive values of both the marginal safety productivity of firm safety investment (i.e., $\frac{dp}{dS} < 0$, since the sign of $\frac{dp}{dS}$ is the opposite of the sign of the marginal productivity of firm safety investment) and the marginal product of safety investment (i.e., $\frac{\partial Q}{\partial S} > 0$). Both of the aforementioned values can be slightly positive (or of opposite signs, i.e., one positive and the other negative) and we can have $\frac{\partial S}{\partial \delta} > 0$, however, as long as $\left(\frac{dp}{dS}A - \frac{\partial Q}{\partial S}\right)(1 + \beta\delta) > -1$. When both the marginal safety*

any individual accident. Whether the conclusions of Peltzman (1975) in the particular context of automobile safety are correct — and there is substantial debate regarding their reliability (see, e.g., Joksch (1976); Peltzman (1976); Robertson (1977); Crandall and Graham (1984)) — is irrelevant here, since I do not rely on his statistical methodology at all.

[32]For an industry in decline with net firm exit — this is the coal industry in the second decade of the 21st century — the assumption of zero profits, rather than just zero marginal profits, is not as unrealistic as it might otherwise be. The notion that coal miner labor markets are perfectly competitive is more specious and discussed briefly in Appendix C.

[33]Note that the safety benefits of fewer fallen phalanges would be accounted for by terms in $\frac{dp}{dS}$. Even if $\frac{\partial Q}{\partial S} < 0$, a safety investment might still be economical.

[34]Full derivations of this and other non-trivial results presented in this section, as well as some underlying regularity assumptions pertaining to the "niceness" of partial derivatives, are in Appendix B.

productivity of firm safety investment and the marginal product of safety investment are negative, it is always the case that $\frac{\partial S}{\partial \delta} > 0$.

The intuition of this proposition is as follows. The nature of the sensitivity of firm safety investments to the probability of a second period depends on the degree and direction of safety-output complementarity and safety-specific returns to safety investments. Restricting analysis to the case where $\frac{dp}{dS} < 0$, a firm can face two scenarios. In both cases, the firm confronts a cost S of safety investment in the first period. Then the firm can either face an additional benefit ($\frac{\partial Q}{\partial S} > 0$) or an additional cost ($\frac{\partial Q}{\partial S} < 0$). When $\frac{\partial Q}{\partial S} < 0$, two costs are incurred in the first period, and benefits of safety investment can be thought of as more heavily distributed to the second period (during which S is not incurred) depending on the magnitude of $\frac{dp}{dS} < 0$ and the levels of discounting and firm operation lifetime expectation. Under these conditions, S may be increasing in the probability δ of a second period. In other words, the value of a safety investment can be sufficiently low in the first period relative to the second period in this case such that an increase in the probability of a second period raises the value of safety overall enough to warrant an increased safety investment. The intuition for other cases proceeds from similar reasoning around adjusting costs and benefits of safety investments across periods.

3.2 Worker safety decision

From the perspective of the worker, S is exogenous. The worker maximizes utility $U(\cdot)$ by choosing a level of workplace safety effort e, subject to the firm's zero-profit constraint that holds in equilibrium due to perfect competition:

$$\begin{aligned} \max_e U =& (1-p(e)) \cdot U_1(1-e) \\ &+ p(e) \cdot U_2(1-e-l) \\ &+ \rho \cdot \delta \cdot (1-p(e)) \cdot U_3((1-e)i_s + 1 - e) \\ &+ \rho \cdot \delta \cdot p(e) \cdot U_4((1-e)i_s + 1 - e - l) \\ &+ \rho \cdot (1-\delta) \cdot U_5((1-e)i_s) \\ \text{s.t. } Q =& S + p(e)A + \beta \cdot \delta \cdot (Q - p(e)A) \end{aligned} \tag{4}$$

The first term is worker utility in the first period when no accident occurs with probability $1-p$. The second term is worker utility when an accident occurs in the first period with probability p. The third term is worker utility in the second period when no accident occurs with probability $1-p$, discounted to the first period by the worker's discount rate ρ and the probability the firm exists in the second period δ. The fourth term is worker utility in the second period when an accident occurs with probability p, discounted to the first period by the worker's discount rate ρ and the probability the firm exists in the second period δ. The fifth term is worker utility in the second period if the firm shuts down after the first period with probability $1-\delta$, discounted to the first period by the worker's discount rate ρ.

In no-accident states worker utility depends on wages earned in the first period period (normalized to equal 1) minus safety effort e. In the second period, workers have savings from the first period's income that they save and earn interest at a composite rate i_s. In the accident state, a worker incurs an additional utility loss l due to injury. If the firm shuts down, workers are assumed to be temporarily unemployed in the second period (i.e., no wage is earned and workers must rely on savings from the first period).

Simplifying notation, (4) becomes $U = (1-p)U_1 + pU_2 + \rho\delta(1-p)U_3 + \rho\delta pU_4 + \rho(1-\delta)U_5$, where $U' > 0, U'' < 0$. With the firm's zero-profit constraint (the last line of (4)), we can set up a Lagrangian with Lagrange multiplier λ. The first-order condition of this gives us:[35]

$$\begin{aligned} &-\frac{\partial p}{\partial e}[U_1 - U_2 + \rho\delta(U_3 - U_4)] - \lambda\frac{\partial p}{\partial e}A(1-\beta\delta) \\ &= (1-p)[U_1' + \rho\delta(1+i_s)U_3'] + p[U_2' + \rho\delta(1+i_s)U_4'] + \rho(1-\delta)i_sU_5' \end{aligned} \tag{5}$$

This states that marginal benefits of workers' safety investments must equal marginal costs, with marginal benefits on the left-hand side of (5) and marginal costs on the right-hand side.

The marginal costs are the sum of marginal utilities in all five states, weighted by accident probabilities, income (normalized to one) saved from the first period not spent on safety provision, the worker's discount rate, and the probability the firm will exist in the second period.

The marginal benefits are composed of two collections of terms. The first collection of terms is the sum, weighted by the marginal productivity of safety with respect to worker safety effort, of differences in utility between accident and non-accident states in the first period and second period, respectively. The second-period utility is discounted to the first period by the worker's rate of time preference and by the probability the second period exists. The second collection of terms is the marginal utility the worker gets from reduced accident costs (e.g., reduced injury severity). The shadow price λ is the marginal utility of relaxing the firm's zero-profit constraint.

Proposition 3 *Workers invest more in safety the higher the marginal safety productivity of their safety investments and the higher utility loss is in the case of an accident. When the probability of the firm existing in a second period increases, however, the effect on worker safety investment is theoretically ambiguous. If marginal benefits exceed marginal costs following a shock to δ, then worker safety investments will increase. In other words, when the difference in utility between accident and non-accident states is sufficiently large, workers will "self insure" to reduce the spread in utilities between states if the probability of a second period (during which a component of this spread exists) increases.*

Recall that marginal safety productivity of safety investments is positive, i.e., $-\frac{\partial p}{\partial e} > 0$. A small increase in the value of this term will increase the value of the left-hand side of (5), which would be positive (since non-accident states necessarily confer higher utility than

[35] Again, see Appendix B for the full setup and derivation.

accident states, $1 - \beta\delta > 0$, and $\lambda \geq 0$ in any reasonable scenario because additional profit to the firm, *ceteris paribus*, would make the worker at least no worse off). To increase the value of the right-hand side, the worker would need to increase their safety investment to increase U'. This is because an increase in e would reduce U, thereby increasing U' (since $U' > 0, U'' < 0$). By the same reasoning, increasing the accident/non-accident state spread represented by $U_1 - U_2$ and $U_3 - U_4$ will necessitate an increase in e.

3.3 Testable hypotheses and relationships generated by the model

This model generates insights about the directions of the three key relationships pertaining to firm and worker safety investment with respect to firm operation lifetime that are highlighted at the beginning of this section. First is the sign of $\frac{dp}{dS}$ in (1). Second is the sign of $\frac{\partial S}{\partial \delta}$ in (3). Third is the direction of the change in worker safety investments in response to a change in δ, which is implied by (5) and will be denoted $\frac{\partial e}{\partial \delta}$. The propositions indicate both the theoretical ambiguity of the direction of these relationships and conditions under which the signs of these effects might be positive or negative.

In the remainder of this paper I apply the insights of the model to data on underground bituminous coal mines. Estimating $\frac{dp}{dS}$, $\frac{\partial S}{\partial \delta}$, and $\frac{\partial e}{\partial \delta}$ can enable us to reconcile the trends in Figure 1, Panel B. If, for example, $\frac{dp}{dS} < 0$ and $\frac{\partial S}{\partial \delta} > 0$, then a compositional change among nonunion mines toward those with larger values of δ would provide an explanation for the decline of the union safety premium. Knowing the direction of $\frac{\partial e}{\partial \delta}$ allows us to determine the extent to which worker behavior reinforces safety investments made by firms. To this end, the empirical analyses in Section 4 estimate the direction of these three relationships and identify the associated causal effects.

The null hypothesis implicitly assumed for all analyses in Section 4 is one of no effect (i.e., $\frac{dp}{dS} = 0$, $\frac{\partial S}{\partial \delta} = 0$, and $\frac{\partial e}{\partial \delta} = 0$); the alternative hypotheses are two-sided.

I use injury rates to define the accident probability p. Unfortunately, S, e, and δ are not directly observable. A mine's operation lifetime during the period where the relevant economic trends developed (i.e., 2000-2022) is used to define δ. The rate at which firms violate "significant and substantial" safety regulations is assumed to correlate with their safety investments S. Components of the variation in the variable used for S are used to asses levels of e and variation in $\frac{\partial e}{\partial \delta}$.

4 Empirical Analysis

There are four empirical analysis subsections that respectively present four distinct empirical analyses.

The first three subsections estimate the direction of the effects suggested by the model introduced in Section 3. As discussed through the three propositions put forth in Section 3, the directions of all the effects are theoretically ambiguous. First, I estimate an analogue of $\frac{dp}{dS}$ in (1) using a control function approach. Second, I estimate an analogue of $\frac{\partial S}{\partial \delta}$ in (3) using ordinary least squares and two-stage least squares. Third, I again use a control function approach to infer the direction of the change in worker safety investments e in response to a change in δ (i.e., $\frac{\partial e}{\partial \delta}$).

The fourth subsection returns to the union safety premium previously discussed in the context of Figure 1, Panel B. Further, it brings us to an answer to the question motivating this paper: What happened to the union safety premium? I replicate the negative binomial specification used by Morantz (2013) to estimate the union safety premium on subsamples of mines varying according to δ. Taken together with the estimated directions of the three effects, this analysis points to a compositional change of mines toward those with larger values of δ (i.e., longer operation lifetimes) as a primary driver of the decline of the union safety premium.

4.1 Firm safety investments and real safety outcomes

In this subsection, the control function methods described by Imbens and Wooldridge (2007), Wooldridge (2015), and Guo and Small (2016) are used to estimate an analogue of $\frac{dp}{dS}$ in (1).[36]

4.1.1 Control function specification

The outcome variable considered is the count of traumatic injuries at a mine in a quarter. We want to estimate the causal effect that safety investments have on the number of traumatic injuries. As previously mentioned, mine-level safety investments are not directly observable. A mine's rate of S&S violations is used as a proxy for its level of safety investment. Mine safety investment levels — and, likewise, rates of S&S violations — are determined endogenously by the mine. Hence, we have a count outcome variable and a continuous endogenous explanatory variable. The unit of analysis is the mine-quarter. The estimating equation used to determine the sign of $\frac{dp}{dS}$ is therefore nonlinear and of the following form:

$$y_{ijt} = \exp\left(\alpha + \gamma_j + \ln\left(o_{it}^{\beta}\right) + \beta_1 x_{ijt} + \rho v_{ijt} + c_{ijt}\right) \tag{6}$$

Control function estimation has an associated first-stage regression:

$$x_{ijt} = \tilde{\alpha} + \tilde{\gamma}_j + \mathbf{B}\mathbf{z}'_{1,it} + v_{ijt} \tag{7}$$

In (6), y_{ijt} is the count of traumatic injuries for mine i in MSHA mine district j in year-quarter t; α is a constant; γ_j represents MSHA mine district fixed effects; $\ln(o_{it}^{\beta})$ is the exposure term (labor hours) with coefficient constrained to 1; x_{ijt} is the S&S violation rate (violations per 500 labor hours, i.e., 1 quarterly FTE); and c_{ijt} is an error term normalized such that $E[\exp(c_{ijt})] = 1$. The definition, inclusion, and purpose of v_{ijt} are explained below.

[36] These are implemented via `ivpoisson cfunction` in Stata.

In (7), x_{ijt} is the same as in (6);[37] $\tilde{\alpha}$ is again a constant; $\tilde{\gamma}_j$ again represents MSHA mine district fixed effects; $\mathbf{z}_{1,it}$ is a vector of instruments for x_{ijt}; and v_{ijt} is an error term. Further, I define $\mathbf{z}_{1,it}$ to be a strict subvector of $\mathbf{z}_{it}$, where $\mathbf{z}_{it}$ also includes a constant and non-instrument exogenous covariates.

I consider one or both of two instruments for a mine's S&S violation rate, depending on the specification, which are represented by $\mathbf{z}_{1,it}$. The two instruments are, respectively, the number of penalty points a mine accrued in the four quarters prior to t[38] (a lagged instrument) and the inverse S&S violation rate for all mines other than i in MSHA mine district j (an instrument that uses regional variation as a plausibly exogenous shifter of the endogenous explanatory variable). Both instrumental variables are continuous. To identify β_1 in (6) and for the control function estimators to be consistent, the following four assumptions must be satisfied:

1. (*Instrument relevance*) Instruments are correlated with endogeneous variables.
2. (*Instrument exogeneity*) Instruments are uncorrelated with the error term in (6). The orthogonality condition is $E(\mathbf{z}'_{it}c_{ijt}) = \mathbf{0}$.
3. $\{c_{ijt}, v_{ijt}\} \perp \mathbf{z}_{it}|j$.
4. $E(c_{ijt}|v_{ijt}) = \frac{E(c_{ijt}v_{ijt})}{E(v_{ijt}^2)}v_{ijt}$

The first two assumptions are the familiar instrumental variables assumptions also required for 2SLS; the latter two are distinct to control function estimation and concern consistency of estimates. The extent to which these assumptions are satisfied — in particular assumptions 1 and 2, as these are required to interpret estimates of β_1 in (6) as causal effects — is discussed at greater length alongside the presentation of results below.

The "controls" in control function estimation are the residuals $\hat{v}_{ijt}$ from (7) that are included as a covariate in (6). The control function estimation proceeds in two steps. First, parameters in (7) are estimated via OLS and residuals $\hat{v}_{ijt}$ are obtained. Second, $\hat{v}_{ijt}$, along with x_{ijt} and o_{it}^{β}, is included in (6), and parameters are estimated using GMM.[39]

The estimate of β_1 gives the sign of $\frac{dp}{dS}$. The parameter ρ measures the endogeneity of x_{ijt}. As emphasized by Wooldridge (2015), a t-test of $H_0 : \rho = 0$ is valid as a test that x_{ijt} is exogenous. In other words, control function estimation has a test akin to that of Hausman (1978) "baked in."

4.1.2 Results and limitations

Table 2 shows the main estimates of the effect of firm safety investments on safety outcomes. Columns (1) and (2) show estimates from just-identified models where the instruments for a mine's S&S violation rate are the inverse S&S violation rate for all other mines

[37] Unlike 2SLS, predicted $\hat{x}_{ijt}$ from (7) are *not* plugged into (6) for control function estimation.

[38] See Section 2 for detail on how this variable is constructed for the first four quarters of the sample.

[39] A one-step GMM estimator is used. For more technical detail on the estimation procedure, see ivpoisson — Poisson model with continuous endogenous covariates, https://www.stata.com/manuals/rivpoisson.pdf (accessed August 20, 2024).

in the same MSHA mine district and the number of penalty points the mine accrued in the previous four quarters, respectively. Column (3) shows estimates from an over-identified model where both instruments are included. Table 2, Panel A reports IRR (incident rate ratios), which are exponential transformations of estimates of the main parameter of interest β_1 in (6). The estimates suggest that an additional S&S violation per FTE at a mine is associated with an increase in the number of traumatic injuries at the mine of between 36 percent and 118 percent.[40] These increases are significant at a 0.1 percent level with standard errors clustered at the mine level.

Table 2: Effect of S&S Violation Rates on Traumatic Injuries

	(1)	(2)	(3)
A. Traumatic Injury Count			
S&S Viol Rate	1.900***	1.366***	2.175***
	(0.297)	(0.104)	(0.363)
B. S&S Viol Rate			
1 / (S&S Viol Rate in Dist)	-0.0352***		-0.0339***
	(0.005)		(0.005)
Penalty Pts in Prev 4 Qtrs		-0.0205***	-0.00854***
		(0.003)	(0.002)
C. Tests for Endogeneity of Covariates			
S&S Viol Rate	-0.592***	-0.269***	-0.728***
	(0.155)	(0.075)	(0.165)
MSHA Mine District FE	Yes	No	Yes
N	33616	33653	33616

Exponentiated coefficients in Panel A; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note on interpretation of results presented: Panel A reports IRR (incidence rate ratio) coefficients. A coefficient of 1 indicates no change at all in predicted injuries; coefficients between 0 and 1 represent a predicted fall in injuries (e.g., a coefficient of 0.95 represents a 5 percent decline); and coefficients greater than 1 represent predicted increases (e.g., a coefficient of 1.05 represents a 5 percent rise). Hours worked is the exposure term. Coefficients in Panels B and C are presented exactly as estimated.
Unit of observation: The unit of observation is the mine-quarter.
Sample: The sample consists of underground bituminous coal mines from 2000 to 2022 with positive coal production and positive hours worked.

[40] A quarterly FTE is defined as 500 hours worked.

Table 2, Panel C shows the results of the test of $H_0 : \rho = 0$. This null hypothesis is rejected at a 0.1 percent level for all three specifications. This is strong evidence that the S&S violation rate is indeed endogenous. These results both lend credence to an instrumental variables design for overcoming endogeneity bias that might pollute regression estimates and provide some assurance that the model used is not misspecified.

The estimates in Table 2, Panel A have a plausibly causal interpretation as the effect of safety investment on injury probability. For this causal interpretation to hold (i.e., for $\hat{\beta}_1$ to be unbiased), we must have instruments that are both relevant and exogenous. Relevance is given by the strong statistical significance of the first-stage parameter estimates of (7) in Table 2, Panel B. Instrument exogeneity is less certain, but there are clear arguments in favor of the exogeneity of the chosen instruments.

The penalty points instrument captures essentially the same information that using a composite of multiple lagged values of the S&S violation rate would. Reed (2015) argues that using lagged values is an effective estimation strategy if the lagged values do not belong in the estimating equation and if they are correlated with the endogenous explanatory variable. There is not a theoretical justification for including previous penalty points in the estimating equation. The relationships derived from the model developed in Section 3 form the foundation of this paper's empirical analysis and suggest an ambiguous effect of safety investment on accident probability that this subsection attempts to identify. The goal of the estimating equation (6) is to produce an estimate $\hat{\beta}_1$ that can be interpreted as the effect of a mine's safety investments (regulatory violations) on its accidents (injuries). Including previous penalty points in the estimating equation would impede this clean interpretation of the coefficient on S&S violations since, in a sense, it can also be interpreted as something correlated with a mine's (historical) safety investments. Further, there is evidence to suggest that historical safety investments can be reversed by regulatory correction; this acts as an exogenous shock to safety investment that provides variation in S&S violations exploited for identification. As shown by the estimate in column (2) of Table 2, Panel B, an increase in the number of penalty points accrued in the previous four quarters actually predicts a *decline* in a mine's subsequent S&S violation rate. Note that in addition to providing evidence in favor of the validity of the instrument, this suggests that safety regulations are in some sense "working"; penalties assessed result in improved safety outcomes, and, by implication, spur increased safety investments.[41] From Table 2, Panel B, the correlation of the penalty points instrument with the endogenous explanatory variable is obvious, hence it would seem to enable an effective estimation strategy as defined by Reed (2015).

The instrument defined as the inverse S&S violation rate for all other mines in the same MSHA mine district has accepted analogues in the IV literature. For example, Azar, Marinescu, and Steinbaum (2022) instrument for occupation-level labor market concentration with the inverse number of employers in the same occupation in other labor markets. The

[41]In contrast to https://www.npr.org/2019/08/22/752868484/no-link-between-fines-and-safety-in-mines-government-audit-says and https://www.npr.org/sections/thetwo-way/2014/05/14/312528687/regulators-couldn-t-close-u-s-mine-despite-poor-safety-record [[cite properly]]

reasoning there and here is that these instruments exploit variation at a higher level of aggregation than the unit of observation instead of potentially endogenous changes in the explanatory variable within units. To account for persistent variation in levels of S&S violations across MSHA mine districts that are attributable to things like inspector behavior or idiosyncratic district administration characteristics, this instrument is assumed exogenous only conditional on MSHA mine district fixed effects.

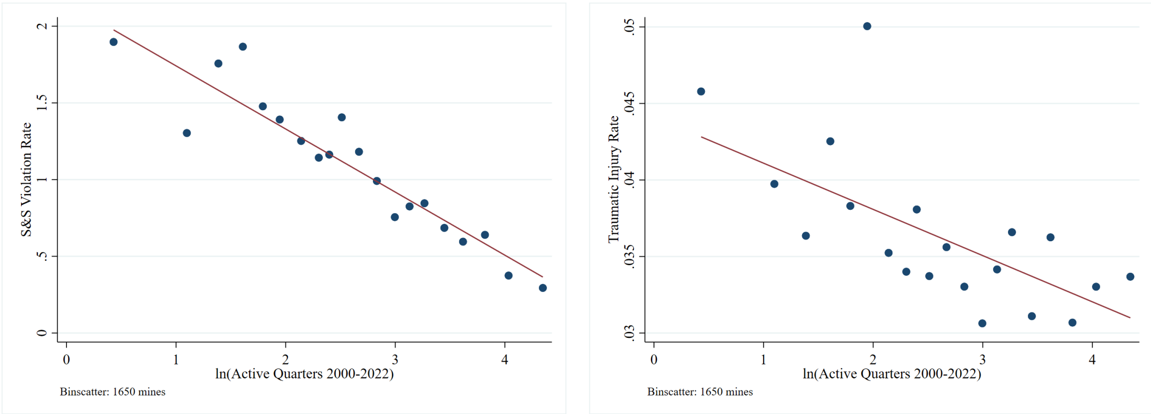
However convincing the arguments for the validity of the instruments might be, it is possible to imagine several exclusion restriction violations that threaten these narratives. If the level of S&S violations in an MSHA mine district is correlated with subsequent structural changes (e.g., entry or exit) that alter the nature of competition between mines, $\hat{\beta}_1$ could be biased. Competition may change the intensity of coal extraction, thereby affecting injury rates. A worst-case scenario for the interpretation of these results would be that previous penalty points provide a signal to workers about their work environment that changes levels of worker safety investment while leaving firm safety investment and S&S violations unchanged. This could conceivably create bias sufficient to flip the sign of the coefficient estimate (or, in this case, move the IRR across the threshold of 1).

If the instruments are valid, the results of this subsection suggest that a mine can reduce accident and injury probabilities via safety investments. That is, there is evidence that, for underground bituminous coal mines in the 21st century in the United States, $\frac{dp}{dS}$ in (1) is negative. Hence, even if there is some moral hazard induced by safety investment (i.e., $\frac{\partial e}{\partial S} < 0$), it is not sufficient to offset the firm's safety investment, and $\left|\frac{\partial p}{\partial e} \cdot \frac{\partial e}{\partial S}\right| < \left|\frac{\partial p}{\partial S}\right|$.

4.2 Safety in firms of different operation lifetimes

Figure 3 shows pronounced, negative associations between mine operation lifetime from 2000-2022 and both safety investment levels (S&S violation rate, shown in Panel A) and real safety outcomes (traumatic injury rate, shown in Panel B). The pattern in Figure 3, Panel A suggests that $\frac{\partial S}{\partial \delta}$ in (3) is positive, and the pattern in Panel B is consistent with this and the evidence presented in the previous subsection that $\frac{dp}{dS} < 0$.[42] This subsection aims to identify a causal effect of mine operation lifetime on safety investment and injury probability using OLS (ordinary least squares) and 2SLS (two-stage least squares) estimators.

[42]If $\frac{dp}{dS} < 0$ and $\frac{dS}{d\delta} = \frac{\partial S}{\partial \delta} > 0$, then $\frac{dp}{d\delta} = \frac{dp}{dS}\frac{dS}{d\delta} < 0$.



(a) S&S Violation Rate vs. Mine Operation Lifetime

(b) Traumatic Injury Rate vs. Mine Operation Lifetime

Figure 3: Relationship between Operation Lifetime and Mine Safety Investments and Outcomes

4.2.1 OLS and 2SLS specifications

The outcome variables considered are either the rate of S&S violations at a mine or the rate of traumatic injuries. Both rates are defined over all the mine's active quarters from 2000-2022. The unit of analysis is the mine (aggregated across all quarters from 2000-2022). We want to estimate the causal effect that mine operation lifetime during the relevant period (from 2000-2022) has on these rates. The baseline, structural model is of the following form:

$$y_{ij} = \alpha + \gamma_j + \beta_1 x_i + \epsilon_{ij} \tag{8}$$

In (8), y_{ij} is either the S&S violation rate or traumatic injury rate (violations or injuries per 2,000 labor hours, i.e., 1 FTE) for mine i in MSHA office region j; α is a constant; γ_j represents MSHA office fixed effects; x_i is the natural logarithm of the number of quarters that mine i is active from 2000-2022; and ϵ_{ij} is an error term.

Identification for regular OLS comes primarily from the validity of the assumption that $E(\epsilon_{ij}|(\cdot)) = 0$ for all values of the regressors $(\cdot)$. Since mine operation lifetime is determined endogenously by the mine — and possibly other omitted confounding variables — this identifying assumption is unlikely to hold. To overcome these challenges, I instrument for x_i. Estimation is done via regular 2SLS. I consider one of two instruments for the number of quarters a mine is active from 2000-2022: the inverse of the average number of quarters from 2000-2022 across all mines other than i in MSHA office region j (an instrument that uses regional variation as a plausibly exogenous shifter of the endogenous explanatory variable) and the maximum height (in inches) of a mine's coal seam from 2000-2022 (an instrument that exploits plausibly exogenous geological variation across mines).

Instrument validity comes from instrument relevance (i.e., instruments must be correlated with x_{ij} in (8)) and instrument exogeneity (i.e., instruments must be uncorrelated with the error term in (8)). The extent to which these assumptions are satisfied is discussed alongside the presentation of results below.

The estimate of β_1 gives the sign of $\frac{\partial S}{\partial \delta}$ (if y_{ij} is the S&S violation rate) or $\frac{\partial p}{\partial \delta}$ (if y_{ij} is the traumatic injury rate).

4.2.2 Results and limitations

Table 3 shows the main estimates of the effect of firm operation lifetime on safety investment and safety outcomes, respectively. The coefficient estimates reported are estimates of β_1 in (8). Columns (1)-(4) show estimates of the effect of mine operation lifetime on S&S violation rates. For a 10 percent increase in the number of active quarters, the S&S violation rate declines by between 0.0309 and 0.0392 violations per FTE when estimated via OLS and between 0.0182 and 0.143 violations per FTE when estimated via 2SLS.[43] These effects are all significant at a 0.1 percent level with heteroskedasticity-robust standard errors.

Table 3: Effect of Mine Operation Lifetime on Safety Investments and Outcomes

	S&S Violation Rate				Traumatic Injury Rate			
	(1) OLS	(2) OLS	(3) 2SLS, MSHA Office	(4) 2SLS, Coal Seam	(5) OLS	(6) OLS	(7) 2SLS, MSHA Office	(8) 2SLS, Coal Seam
ln(Active Quarters 2000-2022)	-0.411***	-0.324***	-0.191***	-1.502***	-0.00302	-0.00415	-0.00523**	0.00271
	(0.063)	(0.063)	(0.031)	(0.222)	(0.003)	(0.003)	(0.002)	(0.006)
MSHA Office FE	No	Yes	Yes	No	No	Yes	Yes	No
First stage F-stat.			123.7	109.3			123.7	109.3
N	1650	1650	1649	1204	1650	1650	1649	1204

Heteroskedasticity-robust standard errors are in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

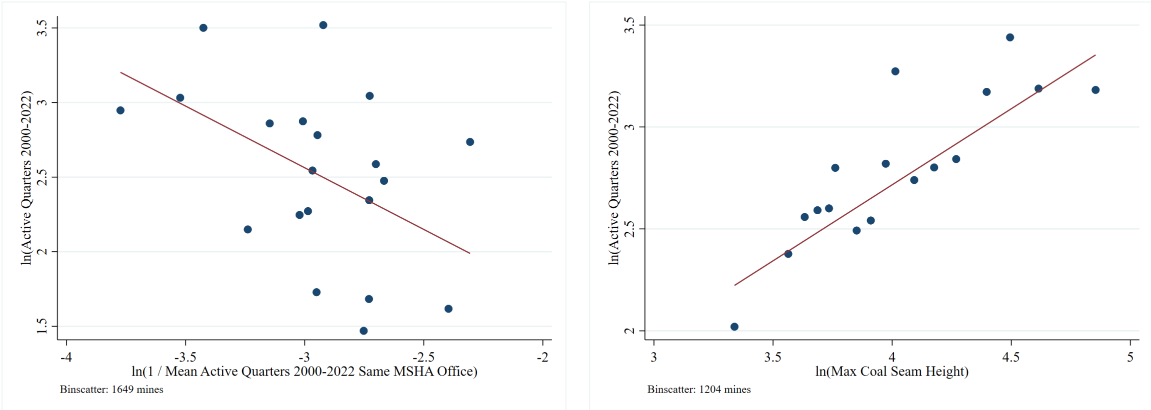
Unit of observation: The unit of observation is the mine.
Sample: The sample consists of underground bituminous coal mines from 2000 to 2022 with positive coal production and positive hours worked.

Columns (5)-(8) of Table 3 show estimates of the effect of mine operation lifetime on traumatic injury rates. Neither the OLS estimates in columns (5)-(6), nor the 2SLS estimate in column (8) with a mine's active quarters instrumented by its maximum coal seam height, are statistically significant at a 5 percent level. Column (7) shows that, for a 10 percent increase in the number of active quarters, the traumatic injury rate declines by 0.000498 injuries per FTE when the number of active quarters at a mine is instrumented by the inverse of the average number of active quarters across all other mines in the same MSHA office region. This estimate is significant at a 1 percent level with heteroskedasticity-robust standard errors.

The IV models in columns (3)-(4) and (7)-(8) of Table 3 are all just-identified. As previously mentioned, mine operation lifetime is endogenously determined by the mine. Therefore, the OLS estimates in columns (1)-(2) and (5)-(6) are likely biased due to omitted confounding variables. Simultaneity bias may also distort estimates since rates of violations injuries may affect a mine's decision to remain in operation. For the 2SLS estimates to have a credibly causal interpretation (i.e., for $\hat{\beta}_1$ from (8) to be unbiased), we must have instruments that are both relevant and exogenous.

[43] For level-log regressions, a 10 percent increase in an explanatory variable with coefficient estimate $\hat{\beta}$ means there is a predicted change in the outcome of $\hat{\beta} \times \ln(1.1)$ units.

Instrument relevance is satisfied by the instruments' strong correlation with the endogenous explanatory variable. This is shown in Figure 4 and through the first-stage F-statistics reported in Table 3, all of which exceed 100.



(a) MSHA Office Variation IV

(b) Coal Seam Height IV

Figure 4: IV First Stages for Operation Lifetime Effect on Mine Safety Investments and Outcomes

The argument for exogeneity is, of course, more complicated. The merits and caveats of the instrument constructed as the inverse of the average number of active quarters across all other mines in the same MSHA office region are the same as the instrument used in the previous section that exploited variation at the MSHA mine district level. In particular, this instrument is promising because it exploits variation at a higher level of aggregation than the unit of observation instead of potentially endogenous changes in the explanatory variable within units. Possible exclusion restriction violations may occur because, among other things, structural changes caused by the instrument that are correlated with the outcome but independent of the endogenous explanatory variable. Note that this instrument is assumed valid conditional on MSHA office fixed effects (i.e., the level of the instrument).

There is precedence in the IV literature for geological instruments that are similar to the coal seam height instrument I use here. For example, Levy and Moscona (2020) use the distance to subterranean bedrock as an instrument for local population density. Further, there is a strong theoretical justification for using coal seam height as a shifter of mine operation lifetime. Wellmer and Scholz (2018) describe determinants of a mine's optimal lifetime and note: "In practice, the optimal lifetime is assessed according to Taylor's Rule an empirically affirmed rule of thumb calculation based on the 'total tonnage expected.'" Taylor (1977), creator of the eponymous rule, defines optimal mine lifetime as monotonically increasing in expected reserve tonnage. Expected reserve tonnage is not observable in publicly available data at the mine level for underground bituminous mines, so coal seam height — a direct measure of the size of the coal deposit and, by implication, a measure we would expect to be tightly correlated with reserve tonnage — is used as a proxy. A pattern consistent with Taylor's Rule is shown in Figure 4, Panel B: mine operation lifetime in the sample period is increasing in maximum coal seam height in the sample period.

There are several conceivable issues with the coal seam height instrument. For example, coal seam height could be endogenously determined, since mines are only in operation where there is coal to mine in the first place. I use maximum coal seam height within the sample period in an attempt to mitigate this issue. The maximum (as opposed to the mean, median, or minimum) incorporates unanticipated, positive coal seam shocks that might come from accessing new coal seam height within a mine's lifetime. A more significant exclusion restriction violation that might bias $\hat{\beta}_1$ arises because the height of a mine's coal seam itself could directly affect safety conditions in a mine. Peters, Fotta, and Mallett (2001) find that miners working in mines with lower seam heights risk a higher probability of death as a result of roof falls and powered haulage equipment accidents. On the other hand, coal itself poses a fire hazard, so the risk of accidents related to fire and explosion may increase with coal seam height.[44] Hence, the direction of bias to $\hat{\beta}_1$ is unclear from these safety-related potential exclusion restriction violations. Coal seam height data are not available for all mines in the sample, so some selection bias might also affect $\hat{\beta}_1$.

Given the severity of the exclusion restriction violations that might bias estimates when coal seam height is used as an instrument, the estimates shown in columns (3) and (7) of Table 3 would seem to be the most reliable. These two estimates suggest that increases in mine operation lifetime cause increases in safety investments and reductions in injury probability. That is, there is evidence that, for underground bituminous coal mines in the 21st century, $\frac{\partial S}{\partial \delta}$ in (3) is positive and, relatedly, $\frac{dp}{dS} < 0$. In the context of the model developed in Section 3, this implies that the marginal product of safety investment is either positive and relatively small or negative.

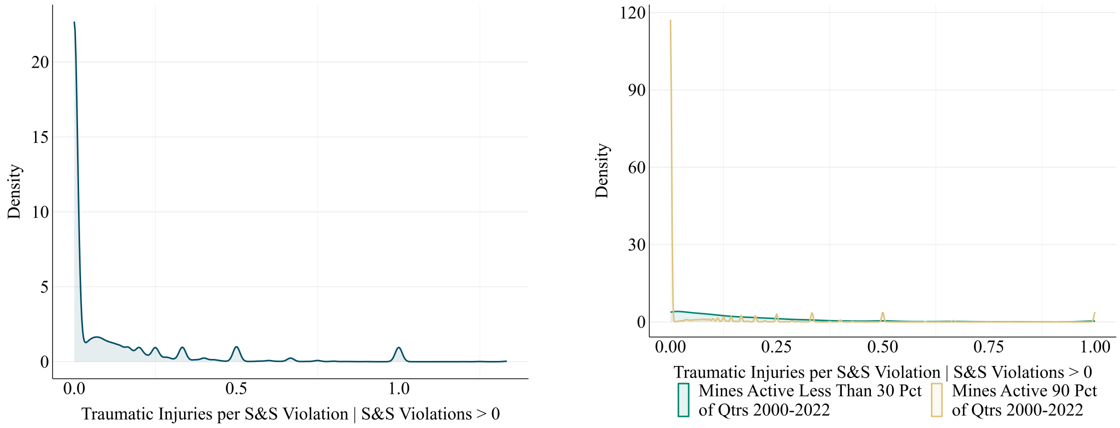
4.3 Worker conversion of firm safety investments over different operation lifetimes

To what extent do workers convert firm safety investments into real safety outcomes? This question is another way of asking what the sign and magnitude of the ambiguous term $\frac{\partial e}{\partial S}$ in (1) is. One statistic that might capture this for coal mining is simply the ratio of traumatic injuries to S&S violations. The distribution of this statistic across all mine-quarters in the sample is shown in Figure 5, Panel A.[45] This subsection is further concerned with the direction of the change in worker safety investments e in response to a change in mine operation lifetime δ (in particular, the partial effect $\frac{\partial e}{\partial \delta}$). Figure 5, Panel B suggests that workers more efficiently convert firm safety investments into real safety outcomes for high values of δ than low values.

Because many mines have quarters without any S&S violations, it is not possible to do a comprehensive study with the statistic plotted in Figure 5 — [[xx]] percent of observations would be discarded. Instead, this subsection employs the same control function estimation methods introduced earlier in an effort to assess how worker safety investments are affected by changes in mine operation lifetime.

[44] University of Calgary, *Energy Education: Coal seam*, https://energyeducation.ca/encyclopedia/Coal_seam (accessed September 19, 2024).

[45] The distributions plotted in Figure 5 are conditional on a mine-quarter's having at least one S&S violation. Otherwise the ratio has 0 in the denominator and is therefore undefined.



(a) Overall

(b) By Operation Lifetime

Figure 5: Distributions of Traumatic Injuries per S&S Violation for Mine-Quarters 2000-2022

4.3.1 Control function specification

This subsection re-estimates (6) and (7) with an additional endogenous explanatory variable and additional associated instruments. The outcome variable is again the count of traumatic injuries at a mine in a quarter. Again let the coefficient on this variable be β_1. As before, we want to estimate the causal effect that safety investments, represented by the S&S violation rate, have on the number of traumatic injuries. To assess how this effect changes with respect to mine operation lifetime, thereby allowing us to learn something about $\frac{\partial e}{\partial \delta}$, a mine's S&S violation rate in a quarter is interacted with the number of quarters it is active in the sample from 2000-2022. Let the coefficient on this variable be β_2. Estimation of the extended version of (6) is again done via GMM.

Versions of the instrumental variables used in this subsection — or, in the case of interaction terms, the components of the instrumental variables — have all already been introduced at some level of aggregation. The instruments, defined for mine i in MSHA mine district j in quarter t, are the number of penalty points i accrued in the four quarters prior to t; the inverse S&S violation rate for all mines other than i in j; the inverse S&S violation rate for all mines other than i in j *interacted with* the inverse of the average number of quarters from 2000-2022 across all mines other than i in j; and the maximum height (in inches) of a i's coal seam from 2000-2022.

As there are two endogenous explanatory variables, there are two first-stage equations, both estimated via OLS, with specifications mirroring (7). Consequently, ρ in (6) is now a vector with two elements we will call ρ_1 and ρ_2. We can then conduct t-tests of $H_0 : \rho_1 = 0$ and $H_0 : \rho_2 = 0$ to test the exogeneity of the explanatory variables (i.e., S&S violation rate and S&S violation rate $\times$ Active Quarters, respectively).

The same assumptions as before must hold for identification and consistency of the control function estimates. For the estimates $\hat{\beta}_1$ and $\hat{\beta}_2$ to have a causal interpretation, instruments must be relevant and exogenous.

4.3.2 Results and limitations

Table 4 shows the main estimates of how the effect of firm safety investments on safety outcomes varies with respect to operation lifetime. Models in all three columns are over-identified.[46] Table 4, Panel A reports IRR, which are exponential transformations of the estimates of the main parameters of interest β_1 and β_2 in the augmented version of (6) I describe above. The IRR estimates shown in the table — denoted $\hat{\beta}_{1,IRR}$ and $\hat{\beta}_{2,IRR}$, respectively — lead to a clean, formulaic interpretation of the effect of violations on injuries that depends on the number of quarters a mine is active from 2000-2022: an additional S&S violation per FTE at a mine is associated with an increase in the number of traumatic injuries at the mine of $\left[\left(\hat{\beta}_{1,IRR} \times \hat{\beta}_{2,IRR}^{\text{Active Quarters}}\right) - 100\right]$ percent.

Estimates in all three columns of Table 4, Panel A are of the same sign and are roughly the same magnitude. Since $\hat{\beta}_{1,IRR} > 1$ and $\hat{\beta}_{2,IRR} < 1$, the main effect of the S&S violation rate on traumatic injuries is positive, and the effect is attenuated as the number of quarters a mine is active increases. The estimates in column (1) suggest that the effect of the S&S violation rate on traumatic injuries becomes negative at 21 quarters of operation in the sample from 2000-2022; column (2) estimates suggest it takes 50 quarters; and column (3) estimates suggest it takes 65 quarters.[47] Further, this pattern is generally robust to variation in the collection of instruments used and MSHA mine district-level fixed effect conditioning. All standard errors reported in Table 4 are clustered at the mine level, and five of the six estimates in Panel A are significant at least at a 5 percent level. Note that the p-value on the interaction term in column (3) of Table 4, Panel A — the only "insignificant" estimate — is approximately 0.055, very close to the standard, 5-percent significance level threshold.

Table 4, Panel D shows the results of the tests of $H_0 : \rho_1 = 0$ and $H_0 : \rho_2 = 0$. Both of these null hypotheses are rejected at least at a 5 percent level for all three specifications. There is therefore sufficient evidence that both the main effect of a mine's S&S violation rate and the interaction with the mine's active quarters are endogenous, as expected. This suggests an instrumental variables approach is indeed necessary to assess causal effects.

[46]Multiple just-identified specifications failed to converge. While some work has been done to provide guidance on workarounds when convergence issues appear with the `poisson` Stata command (Silva and Tenreyro (2011)), the literature concerning similar issues that may crop up with control function estimation by GMM (i.e., `ivpoisson cfunction`) appears less developed.

[47]Note that there are 92 quarters in the sample during which a mine could potentially be active.

Table 4: Effect of S&S Violation Rates on Traumatic Injuries with Mine Operation Lifetime Interaction

	(1)	(2)	(3)
A. Traumatic Injury Count			
S&S Viol Rate	1.357**	1.493***	1.577***
	(0.126)	(0.125)	(0.128)
Act Qtrs × S&S Viol Rate	0.985***	0.992*	0.993
	(0.004)	(0.004)	(0.004)
B. S&S Viol. Rate			
1 / (S&S Viol Rate in Dist)	-0.0354		0.358***
	(0.035)		(0.074)
Penalty Points in Previous 4 Quarters	-0.0113**	-0.00583	-0.00392
	(0.004)	(0.004)	(0.003)
[1 / (Mean Act Qtrs in Dist)] × [1 / (S&S Viol Rate in Dist)]	-2.356	-2.688***	-13.08***
	(1.262)	(0.411)	(2.484)
Max Coal Seam Height	-0.00803*	-0.00533	-0.00517
	(0.004)	(0.003)	(0.003)
C. Act Qtrs × S&S Viol Rate			
1 / (S&S Viol Rate in Dist)	-1.606*		6.367*
	(0.785)		(2.992)
Penalty Points in Previous 4 Quarters	0.183	0.331**	0.365***
	(0.127)	(0.118)	(0.108)
[1 / (Mean Act Qtrs in Dist)] × [1 / (S&S Viol Rate in Dist)]	-29.09	-66.10***	-250.9*
	(29.160)	(14.543)	(99.817)
Max Coal Seam Height	-0.137*	-0.0788	-0.0760
	(0.060)	(0.048)	(0.047)
D. Tests for Endogeneity of Covariates			
S&S Viol Rate	-0.281**	-0.372***	-0.431***
	(0.087)	(0.085)	(0.084)
Act Qtrs × S&S Viol Rate	0.0162***	0.00936*	0.00837*
	(0.004)	(0.004)	(0.004)
MSHA Mine District FE	No	Yes	Yes
N	27642	27642	27642

Exponentiated coefficients in Panel A; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note on interpretation of results presented: Panel A reports IRR (incidence rate ratio) coefficients. A coefficient of 1 indicates no change at all in predicted injuries; coefficients between 0 and 1 represent a predicted fall in injuries (e.g., a coefficient of 0.95 represents a 5 percent decline); and coefficients greater than 1 represent predicted increases (e.g., a coefficient of 1.05 represents a 5 percent rise). Hours worked is the exposure term. Coefficients in Panels B, C, and D are presented exactly as estimated.
Unit of observation: The unit of observation is the mine-quarter.
Sample: The sample consists of underground bituminous coal mines from 2000 to 2022 with positive coal production and positive hours worked.

Recall that both instrument relevance and instrument exogeneity must be satisfied for $\hat{\beta}_1$ and $\hat{\beta}_2$ to be unbiased. The relevance condition is not guaranteed here due to a potential problem of weak instruments that is suggested by the statistical insignificance of some of the first-stage estimates shown in Table 4, Panels B and C. This can bias coefficient estimates in an unknown direction (Stock, Wright, and Yogo (2002)). Further, the exclusion restriction violations discussed in previous subsections still apply to the instruments used here. Hence, the estimates in Table 4, Panel A should be interpreted with some caution.

The previous two subsections presented evidence that mines can reduce injury probability via safety investments and that safety investments are increasing in mine operation lifetime. If the coefficient estimates in Table 4, Panel A are taken as generally unbiased, we can reconcile the fact that estimates in columns (5)-(8) of Table 3 are not nearly as convincing and significant as those in columns (1)-(4). These results show that the data strongly suggest that safety *investments* are increasing in operation lifetime, but the effect on safety *outcomes*, while still positive (i.e., injury rates are decreasing), is not as strong. Estimates in Table 4, Panel A indicate that the effect of mine safety investment is decreasing in mine operation lifetime. One explanation for this within the framework of the model introduced in Section 3 is that there is a reduction in worker safety effort as operation lifetimes increase (i.e., $\frac{\partial e}{\partial \delta} < 0$). Recall from (5) that this will occur if, following a shock to δ, the costs of increasing safety investment e exceed the benefits and that in the two-period setup, firms make a safety investment S once in the first period while workers invest e in both the first and second periods. Since worker safety effort is continuous, it is conceivable that short-term work arrangements create incentives for more per-unit safety investment by workers than longer-term settings.

Given the likely bias in the coefficient estimates reported in this subsection relative to previous subsections' results, there does not seem to be sufficient evidence to fully reject the narrative that longer operation lifetimes cause mines to increase safety investments, which are converted into improved safety outcomes. These results should instead be viewed as useful insofar as they provide some insight into potential causes of heterogeneity in returns to firm safety investment as operation lifetime varies.

4.4 Union safety premium

In this subsection, I replicate and extend the methodology used by Morantz (2013) to estimate the union safety premium over time from 2000-2022 and by mine operation lifetime. This adds statistical rigor to the picture painted by the trends shown in Figure 1, Panel B.

4.4.1 Negative binomial specification

I estimate negative binomial regression models to assess the relationship between union status and both safety outcomes and safety investments.[48] The dependent variables are traumatic injuries and S&S violations. The total number of labor hours is the exposure

[48]Implementation is done with the `nbreg` function in Stata.

term. Independent variables include a union indicator (= 1 when a mine is unionized) and publicly available covariates used by Morantz (2013), who argues that these covariates are "based on prior literature and/or conversations with industry stakeholders, are deemed likely to affect mine safety." The unit of analysis is the mine-quarter. Since I control for mine production at the mine level, the quarter is the most granular unit of time possible to analyze because that is the level of aggregation at which production data are published by MSHA. The dependent variables are count variables and, as shown in Table 1, are over-dispersed. Hence, negative binomial regression, a generalization of Poisson regression, is an appropriate choice to analyze data in this setting when identification comes from selection on observables.[49]

I make a few key departures from a strict replication of Morantz (2013) on additional years of data. First, to determine the evolution of the union safety premium over time, I divide the sample period from 2000-2022 into four continuous, roughly 5-year periods and estimate the negative binomial model on each of these samples. Second, Morantz (2013) only uses safety outcomes (injuries and fatalities) as dependent variables, but I also use safety investments (proxied by regulatory violations). Third, Morantz (2013) interacts the union indicator with mine size in the paper's main specifications and the main effect of the union indicator is treated as the union safety premium. Since mine size is always positive, there is not a huge problem with this approach if the sign of the main union effect and the interaction term are the same; it leads to reporting a conservative estimate of the union safety premium. Since the sign of the main effect and interaction term may not always be the same, especially when the model is estimated on many sub-samples of the data, I also estimate models where the interaction term involving the union indicator is dropped. Fourth and finally, I am interested in how the union safety premium may vary across mines of different operation lifetimes (i.e., as δ as defined in Section 3 varies). To do this, I estimate models for the main specifications reported below where I restrict the sample to include only mines that were active for at least 90 percent of quarters from 2000-2022.

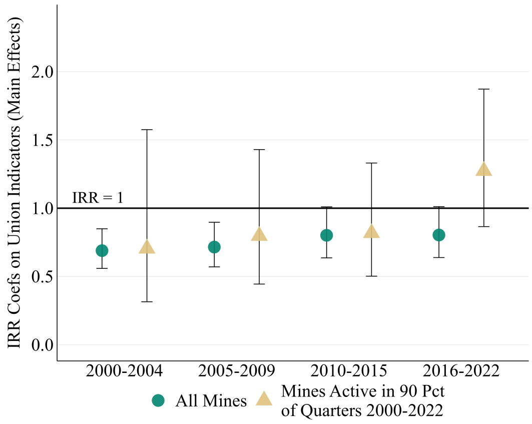
4.4.2 Results and limitations

Figure 6 shows the main estimates, generated from 32 separate regressions, of the union safety premium over time. IRR (incident rate ratios), which are exponential transformations of estimates of the coefficient on the union indicator in negative binomial models, are plotted with 95-percent confidence intervals based on standard errors clustered at the mine level.[50] Recall that an IRR of 1 indicates no change at all in predicted injuries or violations, coefficients between 0 and 1 represent a predicted fall, and coefficients greater than 1 represent predicted increases. An IRR between 0 and 1 therefore indicates a positive union

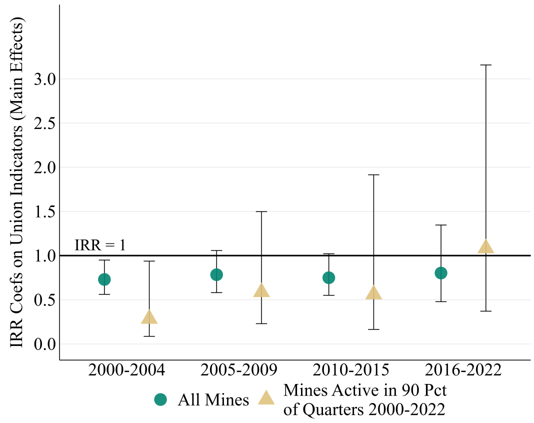
[49] Over-dispersed count data can also be modeled with quasi-Poisson regression models, which weight large and small counts differently than negative binomial models (Ver Hoef and Boveng (2007)). Note that, while there are a substantial number of observations with zero traumatic injuries or zero S&S violations, using "zero-inflated" models is not appropriate because zeros are produced by the same data generating process as non-zeros in this setting.

[50] Confidence intervals appear larger above the IRR = 1 threshold on account of the exponential transformation that occurs.

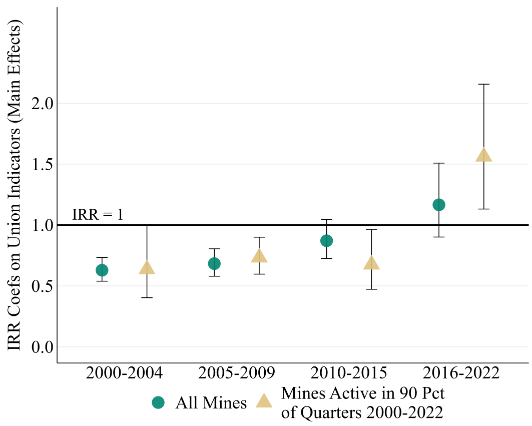
safety premium. Estimates on the full sample are indicated by circles, and estimates on the sample of mines active in at least 90 percent of quarters from 2000-2022 (i.e., those with the highest values of δ) are indicated by triangles. Tables showing estimates for all covariates and robustness checks where the operation lifetime threshold is varied are in Appendix G.[51]



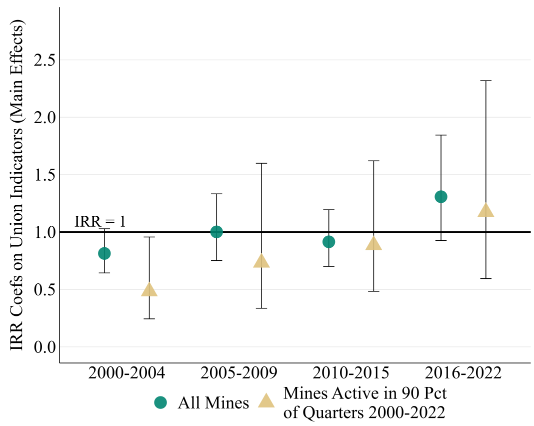
(a) Traumatic Injury Models (Morantz (2013) Specification)



(b) S&S MSHA Violation Models (Morantz (2013) Specification)



(c) Traumatic Injury Models (No Union Interaction)



(d) S&S MSHA Violation Models (No Union Interaction)

Figure 6: Union Safety Premium for All Mines and Mines Active in $\geq$ 90 Pct of Quarters 2000-2022

The trend shown by the green dots in Figure 6, Panels A and C verifies the statistical significance of the narrowing gap between the solid blue and solid green lines in Figure 1, Panel B: the union safety premium declined and disappeared in the first two decades of the 21st century. The pattern suggested by solid blue and dotted red lines in Figure 1, Panel B is also confirmed, but less emphatically. The main union effects estimated for models that also include a union interaction term are plotted in Figure 6, Panel A. These estimates suggest there was never a union safety premium for mines with the longest operation lifetimes in the sample. Figure 6, Panel C shows estimates of the union safety premium from models where the union interaction term is not included. For mines with the longest

[51]The results are generally robust to the threshold of active quarters used. The story does not change much when one of 70, 75, or 80 percent are used instead of 90 percent as the active quarter threshold.

operation lifetimes, there is no statistically significant union safety premium from 2000-2004, then there is a modest positive union safety premium from 2005-2015, and there is actually a *non*union safety premium from 2016-2022; in other words, there is never a stable union safety premium estimated with these models either.

The estimates shown in Figure 6, Panels B and D suggest there was never much of a union safety *investment* premium at any point from 2000-2022 regardless of the model or operation lifetime sample used. In the language of the model in Section 3, $\frac{dp}{dS}$, $\frac{\partial e}{\partial S}$, and $\frac{\partial e}{\partial \delta}$ appear to vary according to union status (albeit not in the same way over time), while $\frac{\partial S}{\partial \delta}$ does not. This suggests unionization affects worker investments in safety more than firm safety investments; in other words, union membership is more important to employees than having a unionized labor force is to firms (at least with respect to workplace safety in the context of underground bituminous coal mining).

How reliable are these results? As far as identifying a causal effect of union status on mine safety outcomes and investment, I do not have high confidence. Despite the large number of observable covariates I select on and fixed effects that I include in my regression models, there is still the risk that this approach allows omitted variable bias to affect the estimates. For example, I am unable to control for potentially important geological characteristics of coal mines or the extent to which contracted labor is used instead of full-time employees are used. Further, union status is almost completely stable within mines over the sample period I examine, so I cannot include mine-level fixed effects. These fixed effects would be collinear with the union indicator, thereby prohibiting estimation of the main coefficient of interest. Further, union status is likely endogenously determined. For example, union miners may have fundamentally different approaches to mine safety compared to nonunion miners. So estimates of any union effect reveal more about safety outcomes at union mines (conditional on covariates) than a true, causal effect of coal mine unions. This is sufficient in the context of this paper, since I am concerned with the union safety premium, a quantity that is distinct from a causal effect of unionization. As defined at the beginning of this paper in Section 1, the union safety premium is simply the average amount by which union mines outperform nonunion mines' safety records.

Notably, Morantz (2013) does not identify a statistically significant union safety premium from 1993-1998 and suggests the most promising hypothesis is "the increasing sophistication and professionalization of UMWA safety programs." When extending the data through 2022, the union safety premium retreats again into nonexistence, and it is for reasons seemingly unrelated to union competence or quality.

5 Conclusion

The contributions of this paper are twofold. First, I documented two new facts about the coal mining industry, which, despite recent declines in demand, remains an economically important industry in the United States that creates a meaningful amount of the nation's energy. I found that the union safety premium declined and disappeared for underground bituminous coal mines in the first two decades of the 21st century. Over the same period, I also found that a consistent union safety premium never existed for mines with the longest operation lifetimes and that the share of mines with longer operation lifetimes increased coincident with this trend.

In addition to documenting these facts, I attempted to explain them. To do this, I developed a model of firm and worker safety investment where the operation lifetime of the firm varies. I then used the model to guide an empirical analysis of underground bituminous coal mines. The results of the empirical analysis pointed to a simple story where where longer operation lifetimes cause mines to have better safety outcomes, and a compositional change in nonunion mines toward those with longer operation lifetimes begets the disappearance of the union safety premium.

Given the inconsistency of estimates relating to worker conversion of firm safety investments into real safety outcomes, this paper should not be interpreted as providing the sole explanation for the disappearance of the union safety premium. An improved model may lead to greater insight on the underlying drivers of the trends than I am able to provide.

An important implication of this paper is that unionization is not the only mechanism able to achieve improved safety outcomes in dangerous jobs. Depending on the bargaining setup, returns on safety investment, and incentives provided by industry-wide shocks, nonunion firms and workers may invest in safety to the same extent they would in the presence of a union — and perhaps even more.

Future work might seek to use more detailed data on miners and mining companies to uncover the precise nature of the bargaining relationship under varying labor organization regimes. Additionally, other industries might be explored to assess whether appropriate policy instruments should be developed to broadly affect all workplaces or on a more targeted, industry-by-industry basis.

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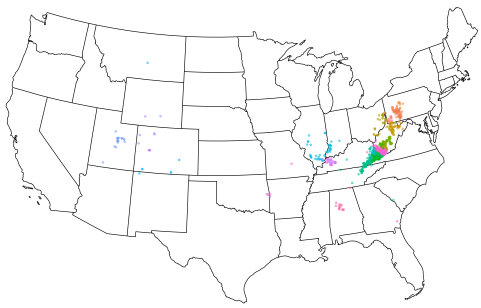
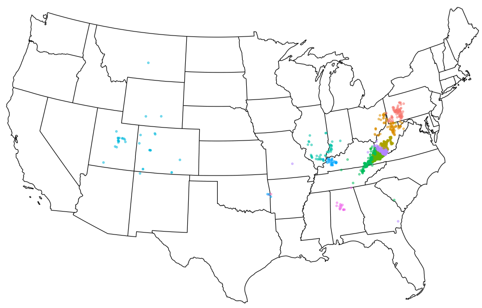
A Data summary statistics and figures



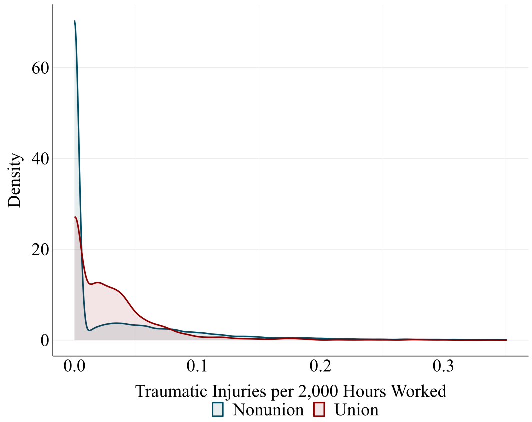
(a) Mines Colored by MSHA Office



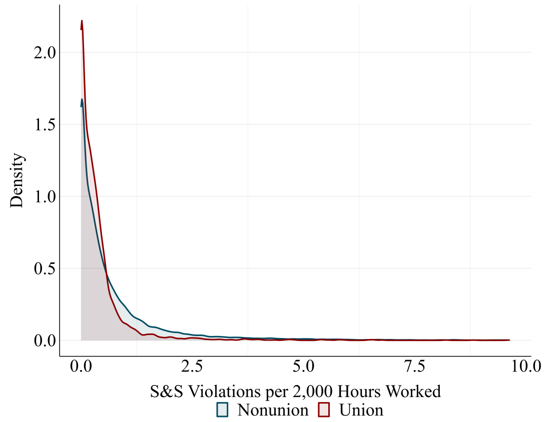
(b) Mines Colored by MSHA Mine District

Figure A1: Active Underground Bituminous Coal Mines in Sample: 2000-2022

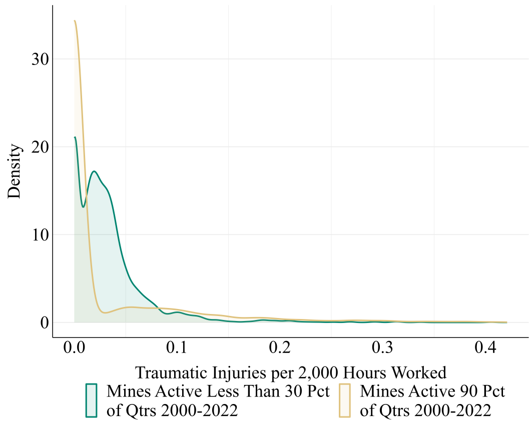
Note: All MSHA offices correspond to a single MSHA district; multiple MSHA offices can map to the same district.



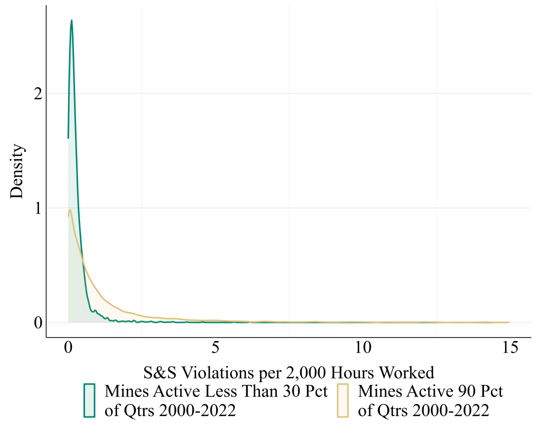
(a) Traumatic Injuries by Union Status



(b) S&S MSHA Violations by Union Status



(c) Traumatic Injuries by Operation Lifetime



(d) S&S MSHA Violations by Operation Lifetime

Figure A2: Distributions of Underground Bituminous Coal Mine Safety Variables for Mine-Quarters 2000-2022

Note: Because of bunching of counts at 0, the density exceeds 1.

B Model derivations

Equation (3)

Recall the firm's profit function (2), here with simplified notation:

$$\pi = Q - S - pA + \beta\delta[Q - pA]$$

Assuming perfect competition, $\pi = 0$. Assuming all partial derivatives exist and are continuous, (3) is derived in the following steps:

$$\begin{aligned}
\frac{d}{d\delta}\left[Q - S - pA + \beta\delta(Q - pA)\right] &= 0 \\
\frac{dQ}{d\delta} - \frac{dS}{d\delta} - \frac{dp}{d\delta}A + \beta\delta\left[\frac{dQ}{d\delta} - \frac{dp}{d\delta}A\right] + \beta[Q - pA] &= 0 \\
\frac{\partial Q}{\partial S}\frac{\partial S}{\partial \delta} - \frac{\partial S}{\partial \delta} - \left(\frac{\partial p}{\partial e}\frac{\partial e}{\partial S}\frac{\partial S}{\partial \delta} + \frac{\partial p}{\partial S}\frac{\partial S}{\partial \delta}\right)A + \beta\delta\left[\frac{\partial Q}{\partial S}\frac{\partial S}{\partial \delta} - \left(\frac{\partial p}{\partial e}\frac{\partial e}{\partial S}\frac{\partial S}{\partial \delta} + \frac{\partial p}{\partial S}\frac{\partial S}{\partial \delta}\right)A\right] &= -\beta[Q - pA] \\
\frac{\partial Q}{\partial S}\frac{\partial S}{\partial \delta} - \frac{\partial S}{\partial \delta} - \frac{\partial S}{\partial \delta}\left(\frac{\partial p}{\partial e}\frac{\partial e}{\partial S} + \frac{\partial p}{\partial S}\right)A + \beta\delta\left[\frac{\partial Q}{\partial S}\frac{\partial S}{\partial \delta} - \frac{\partial S}{\partial \delta}\left(\frac{\partial p}{\partial e}\frac{\partial e}{\partial S} + \frac{\partial p}{\partial S}\right)A\right] &= -\beta[Q - pA] \\
\frac{\partial S}{\partial \delta}\left[-\frac{\partial Q}{\partial \delta} + 1 + \frac{dp}{dS}A\beta\delta\left(\frac{dp}{dS}A - \frac{\partial Q}{\partial S}\right)\right] &= \beta[Q - pA] \\
\frac{\partial S}{\partial \delta}\left[1 + \frac{dp}{dS}A(1 + \beta\delta) - \frac{\partial Q}{\partial S}(1 + \beta\delta)\right] &= \beta[Q - pA] \\
\Rightarrow \frac{\partial S}{\partial \delta}\left[1 + \left(\frac{dp}{dS}A - \frac{\partial Q}{\partial S}\right)(1 + \beta\delta)\right] &= \beta[Q - pA]
\end{aligned}$$

Equation (5)

Recall the worker's utility maximization problem (4):

$$\begin{aligned}
\max_e U =& (1 - p(e)) \cdot U_1(1 - e) \\
&+ p(e) \cdot U_2(1 - e - l) \\
&+ \rho \cdot \delta \cdot (1 - p(e)) \cdot U_3((1 - e)i_s + 1 - e) \\
&+ \rho \cdot \delta \cdot p(e) \cdot U_4((1 - e)i_s + 1 - e - l) \\
&+ \rho \cdot (1 - \delta) \cdot U_5((1 - e)i_s) \\
\text{s.t. } Q =& S + p(e)A + \beta \cdot \delta \cdot (Q - p(e)A)
\end{aligned}$$

With simplified notation, the problem becomes:

$$\max_e U = (1 - p)U_1 + pU_2 + \rho\delta(1 - p)U_3 + \rho\delta pU_4 + \rho(1 - \delta)U_5$$

Subject to the firm's zero-profit constraint that holds in equilibrium due to perfect competition ($Q = S + pA + \beta\delta(Q - pA)$), we have the following Lagrangian:

$$\begin{aligned}
L =& (1 - p)U_1 + pU_2 + \rho\delta(1 - p)U_3 + \rho\delta pU_4 + \rho(1 - \delta)U_5 \\
&+ \lambda[Q - S - pA - \beta\delta(Q - pA)]
\end{aligned}$$

Recall that $U' > 0, U'' < 0$ and that e always enters U as a value subtracted from income (i.e., $\frac{\partial U}{\partial e} = -\alpha U' < 0$, where $\alpha > 0$ is some constant). We can then derive (5) from the first-order condition with respect to e $\left(\frac{\partial L}{\partial e} = 0\right)$:

$$
\begin{aligned}
& - U_1' + pU_1' - \frac{\partial p}{\partial e}U_1 - pU_2' + \frac{\partial p}{\partial e}U_2 - (1+i_s)\rho\delta U_3' + (1+i_s)\rho\delta p U_3' - \rho\delta\frac{\partial p}{\partial e}U_3 \\
& - (1+i_s)\rho\delta p U_4' + \rho\delta\frac{\partial p}{\partial e}U_4 - i_s\rho(1-\delta)U_5' - \lambda\frac{\partial p}{\partial e}A + \lambda\beta\delta\frac{\partial p}{\partial e}A \\
& = 0
\end{aligned}
$$

$$
\begin{aligned}
& - \frac{\partial p}{\partial e}U_1 + \frac{\partial p}{\partial e}U_2 - \rho\delta\frac{\partial p}{\partial e}U_3 + \rho\delta\frac{\partial p}{\partial e}U_4 - \lambda\frac{\partial p}{\partial e}A + \lambda\beta\delta\frac{\partial p}{\partial e}A \\
& = U_1' - pU_1' + pU_2'(1+i_s)\rho\delta U_3' - (1+i_s)\rho\delta p U_3' + (1+i_s)\rho\delta p U_4' + i_s\rho(1-\delta)U_5'
\end{aligned}
$$

$$
\begin{aligned}
\Rightarrow & - \frac{\partial p}{\partial e}[U_1 - U_2 + \rho\delta(U_3 - U_4)] - \lambda\frac{\partial p}{\partial e}A(1-\beta\delta) \\
& = (1-p)[U_1' + \rho\delta(1+i_s)U_3'] + p[U_2' + \rho\delta(1+i_s)U_4'] + \rho(1-\delta)i_s U_5'
\end{aligned}
$$

C Labor market concentration

[[IN PROGRESS: please check the latest version of the draft for potential updates to this section]]

D Forward- and backward-looking expectations of mine operation lifetime

[[IN PROGRESS: please check the latest version of the draft for potential updates to this section]]

E Within- and across-mine variation in mine safety outcomes

[[IN PROGRESS: please check the latest version of the draft for potential updates to this section]]

F Safety and productivity

[[IN PROGRESS: please check the latest version of the draft for potential updates to this section]]

G Full union safety premium tables and mine operation lifetime threshold robustness checks

Table A1: Union Safety Premium Expanded Covariate Report for Mines Active in at Least One Quarter 2000-2022 (Injuries)

	Dependent Variable: Traumatic Injury Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.689***	0.715**	0.801	0.804	0.682***	0.832	0.680***
	(0.073)	(0.083)	(0.094)	(0.094)	(0.060)	(0.082)	(0.054)
Mine Size	0.957	0.937	0.935***	0.942**	0.938	0.940***	0.937***
	(0.035)	(0.036)	(0.018)	(0.022)	(0.032)	(0.016)	(0.018)
Union=1 × Mine Size	0.963	0.985	1.021	1.096**	0.990	1.038	1.028
	(0.041)	(0.036)	(0.028)	(0.033)	(0.032)	(0.027)	(0.024)
ln(Controller Size)	1.042*	1.018	1.014	1.033	1.037**	1.007	1.022*
	(0.018)	(0.018)	(0.016)	(0.025)	(0.014)	(0.015)	(0.011)
Mine Age	1.002	1.002	0.997	0.997	1.002	0.997	0.999
	(0.003)	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.018*	1.006***	1.003	1.004	1.005***	1.004*	1.005***
	(0.008)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	9978	9539	8682	5003	21233	11969	33202

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A2: Union Safety Premium Expanded Covariate Report for Mines Active in at Least One Quarter 2000-2022 (Injuries) — No Union Interaction

	Dependent Variable: Traumatic Injury Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.629***	0.683***	0.871	1.166	0.663***	0.971	0.743***
	(0.049)	(0.057)	(0.081)	(0.153)	(0.047)	(0.084)	(0.045)
Mine Size	0.944	0.933*	0.941***	0.967	0.935*	0.950***	0.945***
	(0.028)	(0.029)	(0.016)	(0.022)	(0.025)	(0.015)	(0.015)
ln(Controller Size)	1.044*	1.018	1.013	1.026	1.038**	1.006	1.021*
	(0.018)	(0.017)	(0.016)	(0.026)	(0.014)	(0.015)	(0.010)
Mine Age	1.002	1.002	0.997	0.997	1.002	0.996	0.999
	(0.003)	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.018*	1.006***	1.003	1.003	1.005***	1.004*	1.005***
	(0.008)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	9978	9539	8682	5003	21233	11969	33202

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A3: Union Safety Premium Expanded Covariate Report for All Mines Active in at Least One Quarter 2000-2022 (MSHA Violations)

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.730*	0.784	0.749	0.803	0.757*	0.779	0.771**
	(0.098)	(0.120)	(0.118)	(0.212)	(0.086)	(0.126)	(0.076)
Mine Size	0.641***	0.780***	0.836**	0.823***	0.757***	0.831***	0.803***
	(0.059)	(0.056)	(0.046)	(0.034)	(0.052)	(0.039)	(0.039)
Union=1 × Mine Size	1.083	1.135	1.070	1.165**	1.147	1.095*	1.105
	(0.104)	(0.090)	(0.054)	(0.060)	(0.089)	(0.047)	(0.056)
ln(Controller Size)	0.786***	0.809***	0.812***	0.803***	0.807***	0.814***	0.807***
	(0.015)	(0.016)	(0.015)	(0.026)	(0.012)	(0.016)	(0.010)
Mine Age	1.004	1.004	1.000	1.005	1.006	1.004	1.004
	(0.004)	(0.004)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)
Productivity	1.000	1.000*	1.000	1.000	1.000*	1.000	1.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.294***	1.023***	1.023***	1.028***	1.031***	1.025***	1.028***
	(0.038)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	9978	9539	8682	5003	21233	11969	33202

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A4: Union Safety Premium Expanded Covariate Report for All Mines Active in at Least One Quarter 2000-2022 (MSHA Violations) — No Union Interaction

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.814	1.001	0.915	1.308	0.956	1.035	0.950
	(0.097)	(0.146)	(0.124)	(0.230)	(0.115)	(0.134)	(0.105)
Mine Size	0.663***	0.816***	0.847***	0.848***	0.796***	0.846***	0.824***
	(0.047)	(0.044)	(0.039)	(0.031)	(0.040)	(0.032)	(0.031)
ln(Controller Size)	0.784***	0.805***	0.810***	0.797***	0.804***	0.811***	0.805***
	(0.015)	(0.015)	(0.014)	(0.026)	(0.012)	(0.015)	(0.010)
Mine Age	1.004	1.004	1.000	1.005	1.006	1.004	1.005
	(0.004)	(0.004)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)
Productivity	1.000	1.000*	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.295***	1.024***	1.024***	1.029***	1.031***	1.026***	1.029***
	(0.038)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	9978	9539	8682	5003	21233	11969	33202

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A5: Union Safety Premium Expanded Covariate Report for All Mines Active in $\geq$ 90 Pct of Quarters 2000-2022 (Injuries)

	Dependent Variable: Traumatic Injury Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.704	0.797	0.818	1.273	0.619	0.835	0.717
	(0.289)	(0.238)	(0.203)	(0.251)	(0.181)	(0.147)	(0.136)
Mine Size	0.898	1.020	1.049	0.991	0.948	1.012	0.986
	(0.058)	(0.068)	(0.026)	(0.036)	(0.041)	(0.036)	(0.028)
Union=1 $\times$ Mine Size	0.965	0.977	0.962	1.055	1.034	1.006	1.018
	(0.109)	(0.067)	(0.029)	(0.048)	(0.059)	(0.039)	(0.036)
ln(Controller Size)	0.888	0.733***	0.810*	1.011	0.804**	0.839*	0.816***
	(0.078)	(0.043)	(0.082)	(0.083)	(0.056)	(0.070)	(0.046)
Mine Age	0.980	1.016*	0.987	1.014	1.001	1.002	1.001
	(0.010)	(0.007)	(0.008)	(0.007)	(0.008)	(0.004)	(0.005)
Productivity	1.000	1.000	1.000**	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.012	1.000	0.999	0.998	1.001	1.001	1.003
	(0.014)	(0.003)	(0.003)	(0.004)	(0.004)	(0.003)	(0.003)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	503	553	676	772	1170	1334	2504

Exponentiated coefficients; standard errors in parentheses clustered at mine level.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A6: Union Safety Premium Expanded Covariate Report for All Mines Active in $\geq$ 90 Pct of Quarters 2000-2022 (Injuries) — No Union Interaction

	Dependent Variable: Traumatic Injury Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.636	0.733**	0.676*	1.562**	0.694*	0.859	0.770
	(0.148)	(0.077)	(0.123)	(0.257)	(0.105)	(0.166)	(0.125)
Mine Size	0.879*	1.002	1.023	1.035	0.970	1.016	0.998
	(0.048)	(0.026)	(0.023)	(0.026)	(0.030)	(0.021)	(0.019)
ln(Controller Size)	0.892	0.737***	0.796*	1.025	0.800***	0.840*	0.816***
	(0.075)	(0.040)	(0.087)	(0.081)	(0.053)	(0.071)	(0.045)
Mine Age	0.982*	1.016*	0.989	1.013	1.000	1.001	1.000
	(0.008)	(0.007)	(0.008)	(0.007)	(0.008)	(0.004)	(0.005)
Productivity	1.000	1.000	1.000*	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.011	1.000	0.998	0.997	1.001	1.002	1.003
	(0.014)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	503	553	676	772	1170	1334	2504

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A7: Union Safety Premium Expanded Covariate Report for Mines Active in ≥ 90 Pct of Quarters 2000-2022 (MSHA Violations)

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.284*	0.586	0.561	1.082	0.581	0.890	0.707
	(0.173)	(0.281)	(0.351)	(0.591)	(0.277)	(0.465)	(0.324)
Mine Size	0.716**	0.815**	0.824*	0.983	0.795**	0.909	0.834***
	(0.079)	(0.061)	(0.068)	(0.072)	(0.057)	(0.059)	(0.039)
Union=1 $\times$ Mine Size	1.223	1.074	1.101	1.023	1.072	1.050	1.054
	(0.158)	(0.092)	(0.086)	(0.073)	(0.075)	(0.070)	(0.053)
ln(Controller Size)	0.890	0.925	0.781	0.921	0.935	0.886	0.939
	(0.092)	(0.106)	(0.129)	(0.103)	(0.080)	(0.096)	(0.078)
Mine Age	1.028	1.014	1.013	1.004	1.022	1.003	1.015
	(0.019)	(0.022)	(0.024)	(0.013)	(0.018)	(0.016)	(0.016)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.148***	1.022***	1.019**	1.013	1.029***	1.015*	1.023***
	(0.027)	(0.006)	(0.007)	(0.008)	(0.005)	(0.006)	(0.005)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	503	553	676	772	1170	1334	2504

Exponentiated coefficients; standard errors in parentheses clustered at mine level.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A8: Union Safety Premium Expanded Covariate Report for Mines Active in ≥ 90 Pct of Quarters 2000-2022 (MSHA Violations) — No Union Interaction

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.483*	0.733	0.886	1.175	0.724	1.082	0.850
	(0.168)	(0.292)	(0.273)	(0.407)	(0.242)	(0.312)	(0.266)
Mine Size	0.799**	0.855**	0.859	0.998	0.828***	0.932	0.857***
	(0.060)	(0.050)	(0.073)	(0.083)	(0.044)	(0.066)	(0.040)
ln(Controller Size)	0.867	0.909	0.827	0.925	0.927	0.897	0.941
	(0.080)	(0.097)	(0.117)	(0.098)	(0.074)	(0.091)	(0.077)
Mine Age	1.016	1.011	1.007	1.003	1.019	1.000	1.012
	(0.016)	(0.021)	(0.024)	(0.012)	(0.017)	(0.016)	(0.015)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.155***	1.023***	1.020**	1.012	1.030***	1.016**	1.024***
	(0.028)	(0.005)	(0.007)	(0.008)	(0.005)	(0.006)	(0.005)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	503	553	676	772	1170	1334	2504

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A9: Union Safety Premium Expanded Covariate Report for All Mines Active in ≥ 80 Pct of Quarters 2000-2022 (Injuries)

	Dependent Variable: Traumatic Injury Count						
	(1) 2000-2004	(2) 2005-2009	(3) 2010-2015	(4) 2016-2022	(5) 2000-2010	(6) 2011-2022	(7) 2000-2022
Union=1	0.470	0.596	0.672	1.061	0.488*	0.796	0.621*
	(0.209)	(0.171)	(0.198)	(0.197)	(0.157)	(0.140)	(0.140)
Mine Size	0.881*	0.948	0.982	0.972	0.915**	0.985	0.957
	(0.054)	(0.045)	(0.030)	(0.025)	(0.030)	(0.025)	(0.024)
Union=1 $\times$ Mine Size	1.046	1.035	1.014	1.073*	1.069	1.022	1.043
	(0.104)	(0.053)	(0.039)	(0.034)	(0.052)	(0.033)	(0.036)
ln(Controller Size)	0.917	0.841**	0.822***	0.947	0.876**	0.847***	0.851***
	(0.053)	(0.049)	(0.045)	(0.057)	(0.042)	(0.042)	(0.033)
Mine Age	0.996	1.012	0.991**	1.005	1.003	0.999	1.001
	(0.006)	(0.006)	(0.003)	(0.005)	(0.005)	(0.004)	(0.003)
Productivity	1.000	1.000	1.000**	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.016	1.002	1.000	1.002	1.003	1.003	1.005*
	(0.014)	(0.003)	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	810	941	1152	1187	1941	2149	4090

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A10: Union Safety Premium Expanded Covariate Report for All Mines Active in ≥ 80 Pct of Quarters 2000-2022 (Injuries) — No Union Interaction

	Dependent Variable: Traumatic Injury Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.533**	0.676**	0.723	1.423*	0.615**	0.881	0.735
	(0.130)	(0.100)	(0.147)	(0.249)	(0.113)	(0.171)	(0.120)
Mine Size	0.903*	0.968	0.989	1.018	0.949	0.996	0.978
	(0.040)	(0.032)	(0.020)	(0.025)	(0.028)	(0.018)	(0.019)
ln(Controller Size)	0.911	0.839**	0.822***	0.943	0.870**	0.846***	0.848***
	(0.048)	(0.048)	(0.045)	(0.059)	(0.040)	(0.041)	(0.032)
Mine Age	0.994	1.011	0.991**	1.004	1.001	0.999	1.000
	(0.005)	(0.006)	(0.003)	(0.005)	(0.005)	(0.004)	(0.003)
Productivity	1.000	1.000	1.000**	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.018	1.002	1.000	1.002	1.004	1.003	1.006*
	(0.015)	(0.004)	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	810	941	1152	1187	1941	2149	4090

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A11: Union Safety Premium Expanded Covariate Report for Mines Active in ≥ 80 Pct of Quarters 2000-2022 (MSHA Violations)

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.205**	0.505	1.084	0.895	0.479	1.117	0.731
	(0.125)	(0.257)	(0.612)	(0.452)	(0.255)	(0.531)	(0.340)
Mine Size	0.660***	0.810***	0.925	0.946	0.790***	0.937	0.873**
	(0.065)	(0.047)	(0.053)	(0.059)	(0.049)	(0.048)	(0.041)
Union=1 × Mine Size	1.289	1.061	0.985	1.049	1.071	1.012	1.021
	(0.169)	(0.080)	(0.069)	(0.077)	(0.082)	(0.062)	(0.056)
ln(Controller Size)	1.035	0.994	0.881	0.806**	1.016	0.874*	0.948
	(0.068)	(0.053)	(0.058)	(0.060)	(0.058)	(0.051)	(0.045)
Mine Age	1.019	1.013	1.005	1.008	1.013	1.006	1.010
	(0.014)	(0.012)	(0.013)	(0.010)	(0.012)	(0.011)	(0.011)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.154***	1.028***	1.021***	1.022**	1.032***	1.019***	1.025***
	(0.027)	(0.005)	(0.004)	(0.007)	(0.006)	(0.005)	(0.005)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	810	941	1152	1187	1941	2149	4090

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A12: Union Safety Premium Expanded Covariate Report for Mines Active in ≥ 80 Pct of Quarters 2000-2022 (MSHA Violations) — No Union Interaction

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.390*	0.617	1.014	1.066	0.593	1.172	0.786
	(0.171)	(0.244)	(0.313)	(0.342)	(0.239)	(0.321)	(0.257)
Mine Size	0.741***	0.834***	0.920	0.966	0.816***	0.941	0.880***
	(0.050)	(0.039)	(0.044)	(0.055)	(0.038)	(0.044)	(0.034)
ln(Controller Size)	1.013	0.991	0.879*	0.804**	1.011	0.875*	0.947
	(0.065)	(0.052)	(0.056)	(0.061)	(0.056)	(0.051)	(0.044)
Mine Age	1.009	1.012	1.005	1.008	1.010	1.006	1.009
	(0.012)	(0.012)	(0.013)	(0.010)	(0.012)	(0.011)	(0.011)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.165***	1.028***	1.021***	1.022**	1.033***	1.019***	1.026***
	(0.027)	(0.005)	(0.004)	(0.007)	(0.005)	(0.005)	(0.005)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	810	941	1152	1187	1941	2149	4090

Exponentiated coefficients; standard errors in parentheses clustered at mine level.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A13: Union Safety Premium Expanded Covariate Report for All Mines Active in ≥ 75 Pct of Quarters 2000-2022 (Injuries)

	Dependent Variable: Traumatic Injury Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.473	0.582^{*}	0.835	0.878	0.495^{*}	0.852	0.623^{**}
	(0.214)	(0.144)	(0.168)	(0.136)	(0.135)	(0.112)	(0.103)
Mine Size	0.893	0.939	0.973	0.962	0.911^{**}	0.978	0.948^{*}
	(0.054)	(0.042)	(0.026)	(0.024)	(0.028)	(0.024)	(0.022)
Union=1 $\times$ Mine Size	1.044	1.029	1.019	1.082^{**}	1.062	1.029	1.048
	(0.101)	(0.049)	(0.033)	(0.031)	(0.048)	(0.030)	(0.033)
ln(Controller Size)	0.917	0.851^{***}	0.817^{***}	0.958	0.886^{**}	0.859^{***}	0.863^{***}
	(0.052)	(0.041)	(0.036)	(0.049)	(0.036)	(0.037)	(0.028)
Mine Age	0.998	1.008	0.994	1.001	1.002	0.998	0.999
	(0.006)	(0.005)	(0.003)	(0.004)	(0.004)	(0.003)	(0.003)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.021	1.003	0.998	1.002	1.004	1.001	1.005^{*}
	(0.014)	(0.004)	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	879	1094	1344	1338	2195	2460	4655

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A14: Union Safety Premium Expanded Covariate Report for All Mines Active in ≥ 75 Pct of Quarters 2000-2022 (Injuries) — No Union Interaction

	Dependent Variable: Traumatic Injury Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.540**	0.644***	0.914	1.186	0.610**	0.964	0.747*
	(0.127)	(0.080)	(0.161)	(0.167)	(0.093)	(0.135)	(0.089)
Mine Size	0.916*	0.955	0.981	1.009	0.942*	0.991	0.969
	(0.035)	(0.030)	(0.020)	(0.027)	(0.026)	(0.018)	(0.019)
ln(Controller Size)	0.910	0.848***	0.817***	0.949	0.878***	0.857***	0.859***
	(0.045)	(0.040)	(0.036)	(0.049)	(0.034)	(0.036)	(0.027)
Mine Age	0.997	1.007	0.994	1.000	1.001	0.997	0.999
	(0.004)	(0.005)	(0.003)	(0.004)	(0.004)	(0.004)	(0.003)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.022	1.003	0.999	1.001	1.005	1.001	1.005*
	(0.014)	(0.004)	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	879	1094	1344	1338	2195	2460	4655

Exponentiated coefficients; standard errors in parentheses clustered at mine level.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A15: Union Safety Premium Expanded Covariate Report for Mines Active in ≥ 75 Pct of Quarters 2000-2022 (MSHA Violations)

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.228*	0.573	0.749	0.643	0.515	0.742	0.641
	(0.140)	(0.232)	(0.395)	(0.254)	(0.212)	(0.303)	(0.228)
Mine Size	0.696**	0.849*	0.927	0.941	0.823**	0.934	0.888*
	(0.081)	(0.060)	(0.052)	(0.052)	(0.057)	(0.045)	(0.043)
Union=1 × Mine Size	1.187	1.019	1.014	1.095	1.025	1.048	1.025
	(0.171)	(0.086)	(0.081)	(0.082)	(0.081)	(0.068)	(0.058)
ln(Controller Size)	0.983	0.969	0.874*	0.753***	0.993	0.831**	0.921
	(0.068)	(0.047)	(0.058)	(0.053)	(0.050)	(0.055)	(0.044)
Mine Age	1.015	1.008	0.999	1.007	1.008	1.001	1.005
	(0.011)	(0.008)	(0.009)	(0.007)	(0.008)	(0.007)	(0.008)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.183***	1.030***	1.019***	1.023***	1.035***	1.018**	1.025***
	(0.039)	(0.005)	(0.005)	(0.007)	(0.005)	(0.006)	(0.004)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	879	1094	1344	1338	2195	2460	4655

Exponentiated coefficients; standard errors in parentheses clustered at mine level.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A16: Union Safety Premium Expanded Covariate Report for Mines Active in ≥ 75 Pct of Quarters 2000-2022 (MSHA Violations) — No Union Interaction

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.371**	0.608	0.795	0.874	0.555*	0.888	0.697
	(0.132)	(0.172)	(0.201)	(0.193)	(0.164)	(0.194)	(0.164)
Mine Size	0.761***	0.856**	0.931	0.975	0.833***	0.949	0.896**
	(0.050)	(0.042)	(0.048)	(0.052)	(0.040)	(0.044)	(0.037)
ln(Controller Size)	0.965	0.968	0.875*	0.747***	0.991	0.830**	0.920
	(0.063)	(0.047)	(0.058)	(0.053)	(0.050)	(0.056)	(0.044)
Mine Age	1.010	1.008	0.999	1.006	1.007	1.001	1.005
	(0.011)	(0.008)	(0.009)	(0.007)	(0.008)	(0.008)	(0.008)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.188***	1.030***	1.019***	1.023***	1.035***	1.018***	1.025***
	(0.039)	(0.005)	(0.005)	(0.007)	(0.005)	(0.006)	(0.004)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	879	1094	1344	1338	2195	2460	4655

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A17: Union Safety Premium Expanded Covariate Report for All Mines Active in ≥ 70 Pct of Quarters 2000-2022 (Injuries)

	Dependent Variable: Traumatic Injury Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.645	0.691	0.785	0.859	0.608	0.853	0.652*
	(0.259)	(0.152)	(0.178)	(0.127)	(0.157)	(0.131)	(0.114)
Mine Size	0.979	0.999	0.970	0.965	0.970	0.975	0.969
	(0.046)	(0.030)	(0.024)	(0.024)	(0.030)	(0.022)	(0.021)
Union=1 $\times$ Mine Size	0.941	0.970	1.005	1.076*	0.994	1.013	1.019
	(0.078)	(0.035)	(0.034)	(0.031)	(0.042)	(0.031)	(0.031)
ln(Controller Size)	0.913	0.865**	0.878**	0.954	0.897**	0.900*	0.889***
	(0.047)	(0.039)	(0.041)	(0.043)	(0.035)	(0.037)	(0.028)
Mine Age	0.994	1.003	0.994	1.001	0.997	0.998	0.997
	(0.006)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)
Productivity	1.000*	1.000	1.000	1.000	1.000*	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.023*	1.005*	1.001	1.002	1.006**	1.002	1.007***
	(0.011)	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1048	1371	1700	1537	2702	2954	5656

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A18: Union Safety Premium Expanded Covariate Report for All Mines Active in $\geq$ 70 Pct of Quarters 2000-2022 (Injuries) — No Union Interaction

	Dependent Variable: Traumatic Injury Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.523**	0.611***	0.807	1.137	0.593**	0.905	0.705**
	(0.123)	(0.080)	(0.141)	(0.152)	(0.096)	(0.119)	(0.084)
Mine Size	0.956	0.988	0.972	1.008	0.968	0.981	0.976
	(0.034)	(0.026)	(0.019)	(0.027)	(0.026)	(0.018)	(0.016)
ln(Controller Size)	0.919	0.866**	0.878**	0.944	0.897**	0.899*	0.887***
	(0.044)	(0.039)	(0.041)	(0.043)	(0.034)	(0.037)	(0.027)
Mine Age	0.996	1.004	0.994	1.000	0.998	0.998	0.997
	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)
Productivity	1.000*	1.000	1.000	1.000	1.000*	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.023*	1.005*	1.001	1.001	1.006**	1.002	1.007***
	(0.010)	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1048	1371	1700	1537	2702	2954	5656

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A19: Union Safety Premium Expanded Covariate Report for Mines Active in ≥ 70 Pct of Quarters 2000-2022 (MSHA Violations)

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.168**	0.435	0.655	0.577	0.423*	0.665	0.580
	(0.108)	(0.199)	(0.367)	(0.225)	(0.185)	(0.274)	(0.215)
Mine Size	0.642**	0.770**	0.922	0.922	0.761**	0.922	0.865**
	(0.089)	(0.073)	(0.050)	(0.051)	(0.075)	(0.045)	(0.047)
Union=1 $\times$ Mine Size	1.343	1.149	1.036	1.118	1.125	1.071	1.064
	(0.219)	(0.132)	(0.087)	(0.087)	(0.120)	(0.072)	(0.071)
ln(Controller Size)	1.052	1.028	0.881*	0.749***	1.047	0.833***	0.939
	(0.066)	(0.051)	(0.050)	(0.042)	(0.051)	(0.045)	(0.038)
Mine Age	1.026	1.012	1.000	1.005	1.012	1.002	1.006
	(0.014)	(0.009)	(0.009)	(0.006)	(0.010)	(0.007)	(0.008)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.130**	1.019**	1.018***	1.026***	1.025***	1.018**	1.022***
	(0.045)	(0.007)	(0.005)	(0.007)	(0.006)	(0.006)	(0.004)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1048	1371	1700	1537	2702	2954	5656

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.

Table A20: Union Safety Premium Expanded Covariate Report for Mines Active in ≥ 70 Pct of Quarters 2000-2022 (MSHA Violations) — No Union Interaction

	Dependent Variable: Significant and Substantial MSHA Violation Count						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	2000-2022
Union=1	0.408*	0.697	0.766	0.844	0.616	0.870	0.720
	(0.146)	(0.213)	(0.209)	(0.178)	(0.190)	(0.192)	(0.176)
Mine Size	0.733**	0.817**	0.931	0.961	0.801***	0.943	0.884**
	(0.072)	(0.052)	(0.045)	(0.049)	(0.053)	(0.041)	(0.038)
ln(Controller Size)	1.025	1.020	0.884*	0.743***	1.038	0.833***	0.937
	(0.061)	(0.049)	(0.050)	(0.042)	(0.048)	(0.045)	(0.037)
Mine Age	1.017	1.010	1.000	1.004	1.010	1.001	1.005
	(0.012)	(0.009)	(0.009)	(0.006)	(0.009)	(0.007)	(0.008)
Productivity	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Penalty Pts Last 4 Qtrs	1.135**	1.020**	1.018***	1.025***	1.026***	1.018***	1.022***
	(0.047)	(0.006)	(0.005)	(0.007)	(0.005)	(0.006)	(0.004)
Mine Subunit FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSHA Mine District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-Quarter FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1048	1371	1700	1537	2702	2954	5656

Exponentiated coefficients; standard errors in parentheses clustered at mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Results presented: The table reports IRR (incidence rate ratio) coefficients in negative binomial regression models.