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

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Abstract

Union coal mines were significantly safer than nonunion ones throughout the first decade of the 21st century. In this paper, I revisit the union-safety relationship in underground bituminous coal mines. First, I show that the union safety premium declined substantially beginning shortly after 2010 and disappeared by 2015. Second, I show that steep declines in the demand for coal shifted the composition of mines toward ones that were in continuous operation longer. Third, I present a model that explains and relates these data patterns. Conceptually, 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. Using mine-level quarterly data, I show that mine safety investments cause a reduction in injury incidence, and longer operation lifetimes cause mines to increase safety investments. At the same time, worker safety investment appears to decline as operation lifetimes increase.

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 is associated with a 14 to 32 percent drop in traumatic injuries from 1993-2010. More recent data call into question the stability of these estimates and indicate that this union safety premium no longer exists.

In this paper, I update and expand on the results of Morantz (2013) by estimating trends in the union safety premium with 12 additional years of data. The rest of the paper offers a partial explanation to the question that naturally emerges from these trends and motivates my analysis: *What happened to the union safety premium?* I hypothesize 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

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[1] Google Scholar reports 132 citations as of November 2, 2024.

operation lifetimes begets the disappearance of the union safety premium. My empirical results, interpreted in the context of the theoretical model I develop and the industry-wide trends I document, support this hypothesis and suggest that the mechanism by which safety outcomes improve is mine safety investments.

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 2022. 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.[3] 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

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

[3]Per Ehrlich and Becker (1972): "Self-insurance and market insurance both redistribute income toward hazardous states, whereas self-protection reduces the probabilities of these states."

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 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 that the model suggests are ex ante ambiguous 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.[4]

The empirical results strongly suggest that mine safety investments cause injury rates to fall and that increases in mine operation lifetime cause mine safety investments to increase. The evidence that longer operation lifetimes cause injury rates to fall is slightly weaker. There appears to be some heterogeneity with respect to mine operation lifetime in the effects of mine safety investments on injury rates. Additional safety investments cause improvements in real safety outcomes for mines with shorter operation lifetimes; as operation lifetimes increase, this effect is attenuated. What may seem to be contradictory about these results can be reconciled by an insight of the theoretical model: worker and firm safety investment levels can move in opposite directions with respect to mine operation

[4]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.

lifetime. My estimates indicate that increases in mine safety investment levels caused by longer operation lifetimes are sufficient to cause better safety outcomes at longer-operating mines. I conclude that reductions in safety efforts by workers attenuate the payoff of these investments but are not sufficient to offset them entirely.

Decisions affecting workplace safety are broadly relevant across multiple fields of economics and social science, and this paper contributes to several literatures. Most obvious 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)).[5] Unions can bring about safer workplace outcomes via a few mechanisms. Collective bargaining, the resources of a national union organization, and the threat of a strike might raise firm safety investment levels. The union might instill a sense of collective identity in members that creates incentives for safer behavior from workers. Unions might also engage in industry-wide lobbying that results in regulations that mandate safer workplaces across union and nonunion workplaces. An important implication of the results presented in this paper is that expectations about operation lifetime at nonunion workplaces can create incentives for safety investment that meet or exceed those that result from unionization. In other words, profitability and prospects of continued operation could be substitutes for formal labor organization in the production of workplace safety. To the best of my knowledge, this insight is a novel contribution of this paper — at least with respect to the coal mine setting.

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)).

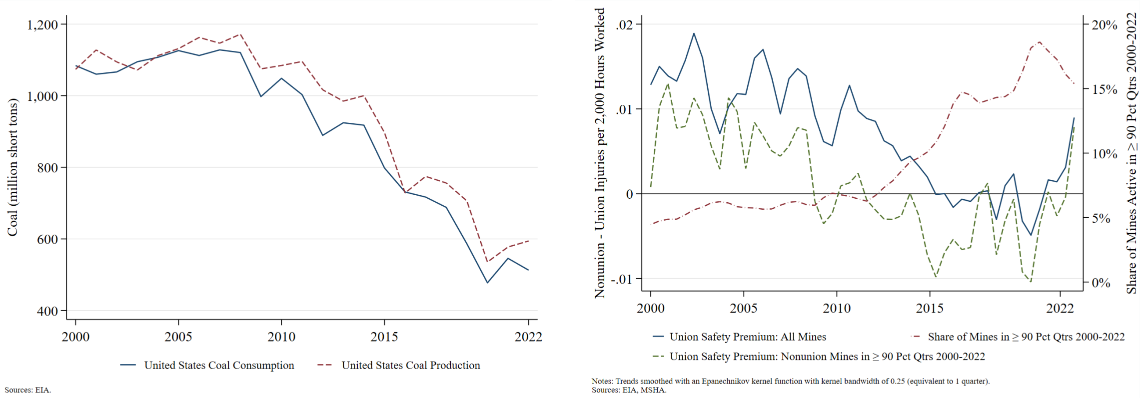
The rest of this paper proceeds as follows. Section 2 describes key, motivating empirical facts, the underground bituminous coal mine empirical setting, and the data used in this paper. Section 3 introduces the model of firm and worker safety investment decisions. Section 4 presents the paper's empirical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

[5] For a more comprehensive review of the literature on coal mine unions, see Morantz (2013).

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.[6] 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,"[7] the economic reality of cheaper substitutes, coupled more recently with billions of federal dollars flowing into green energy technologies and natural gas projects,[8] has made a fantasy of the idea that there will be a rebound in coal demand.[9] This trend is made all the more difficult to reverse 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."[10]



(a) Coal Consumption and Production

(b) Underground Bituminous Coal Mines

Figure 1: 21st Century United States Coal Mining Trends

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

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

[8]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. Acemoglu, Aghion, Barrage, and Hémous (2023) suggest that the shift from coal to natural gas reduces emissions in the short run but increases them in the long run due to incentives firms face to direct innovation away from clean innovation toward shale gas innovation.

[9]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 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.

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

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.[11] 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 labor 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, 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.[12]

There are two key takeaways from Figure 1, Panel B. 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

[11] 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).

[12] 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.

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.[13] 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.

That a stable union safety premium never appears to exist for mines with the longest operation lifetimes, coupled with the fact 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, suggests a few theories.

Perhaps poor safety practices lead mines to rack up fines so significant that it becomes unprofitable to continue operation. But Jordan, Lange, and Linn (2018) find that rising production costs — not increased or accumulated regulatory intervention — 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. For example, one plausible story is that "good managers" operate 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 influence on mine productivity and closure probability.[14] Because management quality is unlikely to have a substantial impact on mine closures, a "good managers" story is unlikely to explain much of the variation in safety records across mines of different operation lifetimes.[15]

[13] Ex ante, it is not obvious whether declining demand will have a greater effect on the intensive or extensive margin of coal production. The data suggest that in this instance the predominant response was mine closure rather than cutbacks in production at existing mines. Future work might focus more specifically on mine churn — specifically in coal mining but perhaps also across the whole distribution of resource extraction sites — and its implications for how changes in demand affect production on the extensive margin. Net exit could broadly be the result of one of two types of churn. On the one hand, a mining industry might have mostly long-term mines, which, in the counterfactual scenario with no demand contraction, would all have remained in operation. In this scenario, net mine exit is the result of mines closing that would have not otherwise closed. On the other hand, the mining industry might have a mix of short- and long-term mines. During a demand contraction, many of the short-term mines might close, but these mines would have closed due to depletion of natural resources even if demand never fell. Additionally, short-term mines that counterfactually would have opened would remain unopened. In this scenario, net mine exit occurs because mines that would have closed anyway closed and mines that would have opened never opened. The appropriate policy response, if any, to address labor shocks to mining towns during demand contraction might depend on the nature of mine churn and labor mobility across short-term mines. Future work that studies this churn might exploit variation within the portfolio of a single, large mining company that holds a mix of short- and long-term mines. The fact that the abundance of natural resources at a mine, as measured by a mine's coal seam height, predicts closure suggests that the setting of this paper is one with a mix of short- and long-term mines.

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

[15] For good managers to be driving better safety records at inframarginal mines, it would have to be the case that the highest quality managers select into jobs at the mines with the lowest probability of closure. It is actually possible to track mine operators over time with the MSHA data I use. In this paper, I focus on the effect of mine operation lifetime itself on safety outcomes, but one area for future work — or future iterations of this paper — would be to test the "good managers" hypothesis empirically. This could be done with an

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 — and the extent to which expectations of longer operation lifetimes cause inframarginal nonunion mines to have better safety records than mines that exited — 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,[16] 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.[17] Yet, while underground mining machine operators still boast a fatality rate more than five times the United States civilian occupation national average,[18] mining coal has become a substantially safer occupation over the last 100 years (see Figure 2).

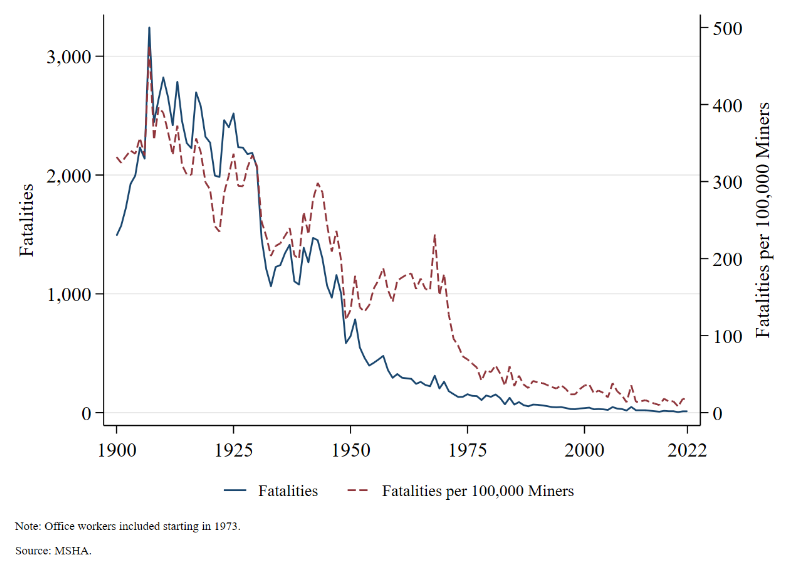


Figure 2: United States Coal Mining Fatalities: 1900-2022

These dramatic gains in safety outcomes can be variously attributed to technological progress, competitive pressures, labor organization efforts, and government regula-

event study design where the effect of managerial quality on safety outcomes is estimated using variation that comes from low-safety mines adding a manager from a high-safety mine, and vice versa.

[16] 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.

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

[18] 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).

tion.[19] Breslin (2010) provides an exhaustive history of federal mining safety and health 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."[20] 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,[21] 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).[22]

Morantz (2013) hypothesizes that injury reporting practices differ substantially between union and nonunion mines.[23] 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).[24]

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.[25]

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

[20]"Union membership rate fell by 0.2 percentage point to 10.1 percent in 2022," *U.S. Bureau of Labor Statistics*, January 24, 2023. Farber, Herbst, Kuziemko, and Naidu (2021) examine the relationship between income inequality and union density.

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

[22]This decline in unionization rates is mirrored by comparable industries, such as construction (Allen (1988)).

[23]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.

[24]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). Future work might estimate the total, discounted cost of an accident to both a mine and society. This number is policy-relevant and an important consideration when setting fines to incentivize safety investment.

[25]Mine Safety and Health Administration, *Mission*, https://www.msha.gov/about/mission (accessed April 14, 2023). Some states have their own additional regulations governing mine safety. As explored by Bradbury

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.[26] Penalties are assessed against mine operators for noncompliance with regulations, with penalty sizes determined by history of violations, size of the business, negligence, seriousness of the offense, and degree of good faith from the operator in correcting the violation promptly.[27] Penalties can be appealed. The average amount ultimately paid per violation across all 936,816 violations included in my analysis is $677.78 in 2022 USD.[28]

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[29]

This implies that it is reasonable to interpret S&S violations as indicative of the absence of materially important safety investments.[30] 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.[31] 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

(2006), state-level regulation creates additional variation that may affect safety outcomes. A close look at state-specific regulation is outside the scope of this paper.

[26]Mine Safety and Health Administration, *Mine Inspections*, https://www.msha.gov/compliance-andenforcement/ mine-inspections (accessed April 14, 2023). The variation created by these additional inspections is not exploited in this paper, but it provides a potential starting point for future related work.

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

[28]This number is adjusted for inflation using the CPI. Federal Reserve Bank of St. Louis, *Consumer Price Index: Total for United States [USACPIALLMINMEI]*, https://fred.stlouisfed.org/series/USACPIALLMINMEI (November 23, 2024)

[29]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).

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

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

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.[32] 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.

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."[33] 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.[34] 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 the data preparation methodology of 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. The majority of mines are in Kentucky, Illinois, Indiana, Pennsylvania, and West Virginia.[35]

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

[32]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.

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

[34]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.

[35]Figure A1 shows the geographic distribution of mines across the United Sates and color codes mines by MSHA office (Panel A) and MSHA mine district (Panel B). 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.

figures that summarize trends and distributions of key variables in the data.

Table 1: Underground Bituminous Coal Mine Characteristics

	N	Mean	Std. Dev.	Minimum	Maximum
Year	33,653	2008.59	6.00	2000	2022
Quarter	33,653	2.49	1.12	1.00	4.00
Union	33,653	0.10	0.30	0	1
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

3 Model

The model introduced here modifies one employed by Guardado and Ziebarth (2019) (which is itself based on the model of "self-protection" described by 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.[36]

[36] In this paper, I model firm and worker safety investment decisions with a "price theory" approach. Future work might analyze firm and worker safety decisions with a more game theoretic framework. This alternative approach could be similar to my current approach in its ability to describe variation in safety investments and outcomes given exogenous incentive structures, but a different model might yield more policy analysis power if the mechanisms of decision making are more accurately captured. Unionization and other bargaining arrangements could also be incorporated. One potential game theory model might involve three types of firms: union, short-term nonunion, and long-term nonunion. Each type of firm plays a repeated game with a worker consisting of T periods in which both firm and worker decide on either high or low safety investment/effort levels. Assume that a worker's dominant strategy is to always choose a high level of safety effort. Workers can punish union firms for under-investing in safety, thereby leading to safety investment by union firms as long as $T > 1$. Short-term nonunion firms are then those for which T is sufficiently small such that the firm "shirks" and has a low safety investment level. Long-term nonunion firms are held accountable by investors and workers that may care about safety reputation (H. B. Christensen et al. (2017); Johnson (2020)) and a higher probability that a single, catastrophically costly accident occurs over a longer operation lifetime with sufficiently large T. This leads long-term nonunion firms to make the same, high safety investments as union firms. This sort of model could be extended to study the effects of unemployment insurance on union members' willingness to strike (a relationship empirically explored by Hutchens, Lipsky, and Stern (1992)) and, consequently, firm safety investments, and it might suggest empirical analyses that assess the sort of variation that causes changes in the prevalence of short-term firms.

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 ($0 < \delta < 1$).[37] 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.

[37] 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 Appendix Figure A7, Panel D 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.

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.[38]

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 an exogenously determined 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, $\pi = 0$.[39] 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 $\left(\frac{\partial Q}{\partial S} < 0\right)$.[40] This leaves us to obtain the following

[38] 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 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.

[39] 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.

[40] 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.

relationship after taking the total derivative of (2) with respect to δ:[41]

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

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

An implication of this proposition is that, under certain conditions, the value of a safety investment can be sufficiently low in the first period relative to the second period 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 reasoning 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. 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:

[41] 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.

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

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 $U = (1-p)U_1 + pU_2 + \rho\delta(1-p)U_3 + \rho\delta p U_4 + \rho(1-\delta)U_5$, 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:[42]

$$
\begin{aligned}
&-\frac{\partial p}{\partial e}[U_1 - U_2 + \rho\delta(U_3 - U_4)] - \lambda\frac{\partial p}{\partial e}A(1-\beta\delta) \\
&= (1-p)[U_1' + \rho\delta(1+i_s)U_3'] + p[U_2' + \rho\delta(1+i_s)U_4'] + \rho(1-\delta)i_s U_5'
\end{aligned}
\tag{5}
$$

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

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

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. When the probability of the firm existing in a second period increases, however, the effect on worker safety investment is theoretically ambiguous.*

Recall that the marginal safety productivity of worker 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 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). Therefore, the benefits of increasing e would exceed the costs.

If marginal benefits exceed marginal costs following a shock to δ, then worker safety investments will increase. The ambiguity of the effect of a shock to δ on e follows from the fact that both the costs and benefits of worker safety investment are increasing in the probability of firm existence in the second period.

Notice that increases in safety investments increase U'. This is because an increase in e would reduce U, and the utility function is concave ($U' > 0, U'' < 0$). Thus, U_2' would increase more than U_1', and U_4' would increase more than U_3'. The costs in the new state of the world after an increase in e are therefore tempered by the associated reduction in p because U_2' and U_4' are discounted by p and U_1' and U_3' are discounted by $1-p$ on the right-hand side of (5).

By the same reasoning, technology that reduces l would increase the values of U_2 and U_4 and decrease the values of U_2' and U_4'. Therefore, reductions in l have an ambiguous effect on worker safety investments since they both decrease the benefits (via a reduction in the accident/non-accident state spread represented by U_1-U_2 and U_3-U_4) and decrease the costs of these investments. If we assume that firm safety investments can affect l, this provides an alternative explanation for the ambiguity of the sign of $\frac{\partial e}{\partial S}$ in (1).

3.3 Testable hypotheses suggested 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.

4 Empirical Analysis

For the purposes of this analysis, I assume a coal mine's rate of S&S violations reflect its safety investments (S in the theoretical model developed in Section 3). In particular, higher safety investments are assumed to imply lower S&S violation rates. Traumatic injury rates are treated as a proxy for a mine's accident probability (p in the theoretical model), and the number of quarters a mine is active during the sample period is treated as a proxy for mine operation lifetime (δ in the theoretical model). It is difficult to associate worker safety investments (e in the theoretical model) with a single variable in the available data, but I deduce the response of worker safety investments to mine operation lifetime from variation in the effect of mine safety investments across specifications. This approach is discussed at greater length below.

First, I estimate the effect of S&S violation rates on traumatic injuries. I find that an additional S&S violation per FTE at a mine causes an average increase in the number of traumatic injuries of between 37 and 118 percent. This means that mine safety investments cause a reduction in the probability of an accident.

Second, I estimate the effect of the number of quarters a mine is active during the sample period (from 2000-2022) on S&S violation rates and traumatic injuries. I find that a 10 percent increase in the number of active quarters causes an average decline of between 0.0182 and 0.143 S&S violations per FTE. Estimated effects on traumatic injuries are not as strong, by one statistically significant estimate suggests that a 10 percent increase in the number of active quarters causes an average decline of 0.00049 traumatic injuries per FTE. Taken together, this means that longer operation lifetimes cause mines to increase safety investments, but longer operation lifetimes only weakly cause real safety outcomes to improve.

Third, I estimate the effect of S&S violation rates on traumatic injuries with a specification where the S&S violation rate is interacted with the number of quarters a mine is active during the sample period. I find that additional S&S violation rates cause increases in traumatic injuries on average for low numbers of active quarters, but this effect becomes insignificant and changes direction for higher numbers of active quarters. This means that the returns to mine safety investments are lower for mines with longer operation lifetimes and suggests potentially heterogeneous treatment effects of mine safety investments on safety outcomes. In light of estimates from other specifications that imply that longer mine operation lifetimes cause mines to significantly increase their safety investments and weakly decrease accident probabilities, these heterogeneous treatment effects seem likely to be caused by declines in worker safety investments in response to longer mine operation lifetimes. The theoretical model of worker and firm safety investments points to two potential mechanisms: expectations of mine operation lifetime itself could be causing a reduction in worker safety effort, or increases in mine safety investments caused by longer operation lifetimes could be inducing workers to cut back on their safety efforts in a way that offsets the mine's investment.

Finally, I estimate the union safety premium itself. The decline in the overall union safety premium illustrated above in Figure 1, Panel B is first shown to be robust to conditioning on the covariates used by Morantz (2013). When the sample is restricted to only mines active in at least 90 percent of quarters from 2000-2022, the union safety premium is not statistically significant from 2000-2004. Interestingly, there is no consistently measurable union safety *investment* premium: in both the sample with all mine-quarters and only those for mines active in at least 90 percent of quarters from 2000-2022, union and nonunion mines invest in safety the same amount on average. The one exception is that union mines make larger safety investments than nonunion mines from 2000-2004, and there is a slight negative trend in the union safety investment premiums over time. Since the average union mine is active about 2.5 more years from 2000-2022 than the average nonunion mine across the entire sample, these results suggest that safety investments and real safety outcomes at union mines may not be as responsive to longer operation lifetimes as at nonunion mines. This could be because unions themselves create sufficiently strong incentives to maintain safety investment levels by mines and workers that other factors do not affect safety investment levels as much as they do at nonunion mines.

Taken together, the results of this paper's empirical analysis paint a picture of the coal mining industry in which longer operation lifetimes cause mines to make additional safety investments. These safety investments are sufficient to cause a reduction in accident probability. This provides an explanation for why declines in demand for coal that led to mine exit and a compositional change in mines toward those with longer operation lifetimes coincided with the disappearance of the union safety premium.

4.1 Mine safety investments and real safety outcomes

In this subsection, I describe the methods used to estimate the effect of S&S violation rates on traumatic injuries. I also report the resulting estimates and discuss their implications.

4.1.1 Empirical framework

I use the control function methods described by Imbens and Wooldridge (2007), Wooldridge (2015), and Guo and Small (2016) to estimate the effect of S&S violation rates on traumatic injuries. For the purposes of this analysis, this is equivalent to estimating the effect of mine safety investments on accident probabilities, a real safety outcome.

The outcome variable is the count of traumatic injuries at a mine in a quarter. The objective is to estimate the causal effect of a mine's rate of S&S violations on traumatic injuries. Mine safety investment levels are determined endogenously by the mine. We thus have a count outcome variable and a continuous endogenous explanatory variable, so an instrumental variables design with a control function approach is the natural choice to identify the coefficient on the S&S violation rate. The unit of analysis is the mine-quarter, and the estimating equation is of the following, nonlinear form:[43]

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

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 2,000 labor hours, i.e., 1 FTE); and c_{ijt} is an error term.[44] The inclusion of v_{ijt} is explained below.

In (7), x_{ijt} is again the S&S violation rate; $\tilde{\alpha}$ 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};[45] and v_{ijt} is an error term.

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.[46] 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.[47]

I use two instruments for a mine's S&S violation rate: the number of penalty points

[43] Alternatively, it might seem reasonable to use an estimating equation of the form: $\ln(y_{ijt}) = \alpha + \gamma_j + \beta_1 x_{ijt} + c_{ijt}$. Approximately 60 percent of mine-quarter observations have 0 reported traumatic injuries, however. Since $\ln(0)$ is undefined, a log-linear model would result in a substantial amount of dropped observations without a clear theoretical justification. Note that one potential extension of this paper's empirical strategy might exploit potential heterogeneity across mines based on a predicted probability of having at least one traumatic injury to improve statistical power. One implementation of this could be employing a machine learning model in the spirit of Einav, Finkelstein, and Mahoney (2023) and allowing the coefficient on the S&S violation rate to vary flexibly based on this predicted outcome. This approach could yield an estimate for some subset of the mines that a log-linear model on all mine-quarters with > 0 traumatic injuries would.

[44] This error term is normalized such that $E[\exp(c_{ijt})] = 1$.

[45] 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.

[46] The control function estimation is implemented via `ivpoisson cfunction` in Stata. 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).

[47] In other words, control function estimation has a test akin to that of Hausman (1978) "baked in."

a mine accrued in the four quarters prior to t[48] (a "lagged instrument") and the inverse S&S violation rate for all mines other than i in MSHA mine district j (a "regional variation instrument"). The identifying assumptions are instrument relevance and exogeneity. Instrument relevance is empirically verified by the strength of the first-stage estimates of $\mathbf{B}$ that are presented below, and both instruments are plausibly exogenous in this setting.

The lagged instrument captures captures essentially the same information that using a composite of multiple lagged values of the S&S violation rate would.[49] 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 here for including previous penalty points in the estimating equation.[50]

The regional variation instrument 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 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.

In the results presented below, I estimate just-identified models separately for each of the two instruments; an over-identified model with both instruments included is also estimated. The estimated coefficients from the main, structural specification are exponentiated and interpretable as IRRs (incidence rate ratios). When the estimate of β_1 is exponenetiated, 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). I calculate heteroskedasticity-robust standard errors clustered at the mine level for all estimates.

[48]For the first four quarters of the sample, the most recent quarter's penalty points are multiplied by the number of missing quarters such that the total number of quarters over which penalty points are summed is still 4.

[49]Lagged penalty points are a better instrument than lagged violations because penalty points incorporate additional information regarding regulatory enforcement that could be an important exogenous shifter of mine safety investment levels.

[50]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 of β_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.

4.1.2 Results

Table 2 shows the main estimates of the effect of mine safety investments on safety outcomes. The estimates in Panel A indicate 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 over that period of between 37 and 118 percent. These increases are statistically significant at a 0.1 percent level. The estimates can be interpreted as causal effects. As discussed above, the instruments for the S&S violation rate are plausibly exogenous, and the significance of the estimates in Panel B indicates that the instruments are relevant.[51] These results mean that mines can reduce the probability of an accident with safety investments. This implies that, even if there is some moral hazard among employees induced by a mine safety investment such that employees cut back on their safety efforts, it is not sufficient to offset improvements to real safety outcomes caused by the mine's investment.[52]

Table 2: Effect of Safety Investments on Outcomes

	(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

Coefficients in Panel A are exponentiated. The unit of observation is a mine-quarter.
Standard errors in parentheses are clustered at the mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

It is worth noticing that the first-stage estimates in Panel B present some evidence that historical safety investment habits can be reversed by regulatory correction.[53] As shown

[51]Table 2, Panel C presents strong evidence that the S&S violation rate is indeed endogenous and that, consequently, an instrumental variables design is necessary for identification. This provides some assurance that the model used is not misspecified. The main concern with respect to identification is a violation of the exclusion restriction. 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, estimates of β_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).

[52]In the language of the theoretical model, $\frac{dp}{dS}$ is negative. Thus, even if $\frac{\partial e}{\partial S} < 0$, $\left|\frac{\partial p}{\partial e} \cdot \frac{\partial e}{\partial S}\right| < \left|\frac{\partial p}{\partial S}\right|$.

[53]In addition to being an interesting pattern in the data, this regulatory correction can be viewed as an

in column (2), 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. This suggests that safety regulations are in some sense "working," since penalties assessed appear to spur increased safety investments.[54]

4.2 Safety in firms of different operation lifetimes

In this subsection, I describe the methods used to estimate the effect of mine operation lifetime on S&S violation rates and traumatic injury rates. I also report the resulting estimates and discuss their implications.

4.2.1 Empirical framework

The outcome variables are the rate of S&S violations and the rate of traumatic injuries at a mine over all active quarters from 2000-2022. The objective is to estimate the causal effect of the number of quarters a mine is active during the sample period (from 2000-2022) on these rates. The unit of analysis is the mine, and 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 use an instrumental variables design. Estimation is done via regular 2SLS.

I use 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 (a "regional variation instrument") and the maximum height (in inches) of a mine's coal seam from 2000-2022 (a "geological instrument"). The identifying assumptions are instrument relevance and exogeneity. Instrument relevance is empirically verified by the strength of the first stage, indicated by the first-stage F-statistic presented below, and both instruments are plausibly exogenous in this setting.

The regional variation instrument is plausibly exogeneous for the reasons already discussed above. It is only assumed valid conditional on MSHA office fixed effects (i.e., the level of the instrument).

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exogenous shock to safety investment that provides variation in S&S violations exploited for identification

[54] This observation is in contrast to Howard Berkes and Robert Benincasa, "Mines No Safer Despite $1 Billion In Fines, Federal Audit Says," *NPR*, August 22, 2019; Anna Boiko-Weyrauch and Howard Berkes, "Regulators Couldn't Close U.S. Mine Despite Poor Safety Record," *NPR*, May 14, 2014.

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 Appendix Figure A7, Panel D: mine operation lifetime in the sample period is increasing in maximum coal seam height in the sample period.

While the coal seam height instrument has many appealing features, it also entails several conceivable and meaningful exclusion restriction violations that may encourage favoring estimates from 2SLS specifications that employ the regional variation instrument.[55] 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.[56] A more significant exclusion restriction violation that might bias $\hat{\beta}_1$ in an ambiguous direction, particularly when the outcome is the traumatic injury rate at a mine, arises because the height of a mine's coal seam itself could directly affect real safety outcomes 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.[57]

In the results presented below, all IV specifications are just-identified. The estimated models are level-log regressions, so a 10 percent increase in the number of quarters a mine is active means there is a predicted change in the outcome of $\hat{\beta}_1 \times \ln(1.1)$ units. I calculate heteroskedasticity-robust standard errors for all estimates.

4.2.2 Results

Table 3 shows the main estimates of the effect of mine operation lifetime on mine safety investments and safety outcomes. A 10 percent increase in the number of quarters a mine

[55] An additional threat to identification is a consequence of the fact that coal seam height data are not available for all mines in the sample. Thus, $\hat{\beta}_1$ may also be afflicted by some selection bias.

[56] 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.

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

is active is associated with declines in the S&S violation rate of 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.[58] These declines are all statistically significant at a 0.1 percent level. The effect of mine operation lifetime on real safety outcomes is not statistically significant at a 5 percent level when estimated with OLS or with 2SLS when the geological instrument is used. When the regional variation instrument is used, however, I estimate that, for a 10 percent increase in the number of active quarters, the traumatic injury rate declines by 0.000498 injuries per FTE.[59] This estimate is significant at a 1 percent level.

Table 3: Effect of 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

The unit of observation is a mine. Heteroskedasticity-robust standard errors are in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The 2SLS estimates can be interpreted as causal effects. As discussed above, the instruments for mine operation lifetime are plausibly exogenous, although there are good reasons to place more weight on estimates from specifications with the regional variation instrument than those with the geological instrument. Instrument relevance is strongly satisfied, since the first-stage F-statistics reported in Table 3 all exceed 100.[60] This means that increases in mine operation lifetime cause increases in safety investments and reductions in injury probability.[61] The effect on safety investments, however, is more robust.

The results up to this point strongly indicate that safety investments cause reductions in accident probability on average over the whole sample and longer operation lifetimes cause increases in safety investments. But longer operation lifetimes only weakly reduce accident probabilities. This may be an indicator of heterogeneous treatment effects of safety investments on accident probability with respect to operation lifetime. Further evidence of this is presented below and interpreted as the result of reductions in worker safety investments with respect to operation lifetime.

4.3 Worker conversion of firm safety investments over different operation lifetimes

In this subsection I describe the methods used to estimate the effect of S&S violation rates on traumatic injuries when the S&S violation rate is interacted with the number of quarters a mine is active during the sample period. I also report the resulting estimates and discuss

[58] There are an average of 0.3243 S&S violations per FTE across the entire sample.

[59] There are an average of 0.03319 traumatic injuries per FTE across the entire sample.

[60] Binscatters in Appendix E show the sign of the first-stage relationships.

[61] In the language of the theoretical model, $\frac{\partial S}{\partial \delta}$ is positive and, relatedly, $\frac{dp}{dS} < 0$. This implies that the marginal product of safety investment is either positive and relatively small or negative.

their implications with respect to heterogeneous treatment effects of mine safety investments and the response of worker safety effort levels to changes in operation lifetime.

4.3.1 Empirical framework

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. The objective is 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, 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 representing the main effect again be β_1 and the coefficient on the interaction term be β_2.[62]

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. The familiar assumptions of instrument relevance and exogeneity must hold for estimates of β_1 and β_2 to be identified.

In the results presented below, all specifications are over-identified.[63] The estimated coefficients from the main, structural specification are exponentiated and interpretable as IRRs. The exponentiated estimates of β_1 and β_2 enable a formulaic interpretation of the results: 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. I calculate heteroskedasticity-robust standard errors clustered at the mine level for all estimates.

4.3.2 Results

Table 4 shows the main estimates of how the effect of firm safety investments on safety outcomes varies with respect to operation lifetime. The estimates in Panel A indicate that the main effect of the S&S violation rate is greater than one and the coefficient on the interaction term is less than one. Five of the six estimates in Panel A are significant at

[62] As there are two endogenous explanatory variables, there are two first-stage equations, 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).

[63] 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.

Table 4: Effect of Safety Investments on Outcomes (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

Coefficients in Panel A are exponentiated. The unit of observation is a mine-quarter.
Standard errors in parentheses are clustered at the mine level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

least at a 5 percent level.[64] This means that 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.[65] In other words, the real safety returns to mine safety investments are decreasing in operation lifetime.

[64]The p-value on the interaction term in column (3) of Panel A — the only "insignificant" estimate — is approximately 0.055, very close to the standard, 5-percent significance level threshold.

[65]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. There are 92 quarters in the sample during which a mine could potentially be active.

At first glance, these results might appear contradictory in light of evidence presented in previous subsections that mines can reduce injury probability via safety investments and that safety investments are increasing in mine operation lifetime. These first appearances can be reconciled by the fact these heterogeneous treatment effects of mine safety investments on safety outcomes can be caused by *workers* cutting back on their safety investments in response to longer mine operation lifetimes.[66] In the two-period setup of the theoretical model, mines make a safety investment once in the first period while workers expend safety efforts in both the first and second periods. Since worker safety effort is continuous through the lifetime of a mine, it is conceivable that short-term work arrangements create incentives for more per-unit safety investment by workers than longer-term settings.[67]

While it is reassuring that the estimates in Table 4 are consistent with the other results I present in this paper, causal interpretations should be accepted with some caution. The statistical insignificance of some of the first-stage estimates shown in Panels B and C is evidence of weak instruments. This indicates a potential lack of instrument relevance, which can bias coefficient estimates in an unknown direction (Stock, Wright, and Yogo (2002)).[68]

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 Empirical framework

I estimate negative binomial regression models to assess the relationship between union status and both safety outcomes and safety investments.[69] The dependent variables are traumatic injuries and S&S violations. The total number of labor hours is the exposure 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, "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

[66] In the language of the theoretical model, $\frac{\partial e}{\partial \delta} < 0$.

[67] There are, of course, other explanations. In particular, concerns about reputation may influence mine safety investments over longer operation lifetimes. Workers may respond to these investments by reducing their safety efforts.

[68] Table 4, Panel D shows estimates with which the null hypothesis of explanatory variable exogeneity can be 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.

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

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.[70]

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. 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.

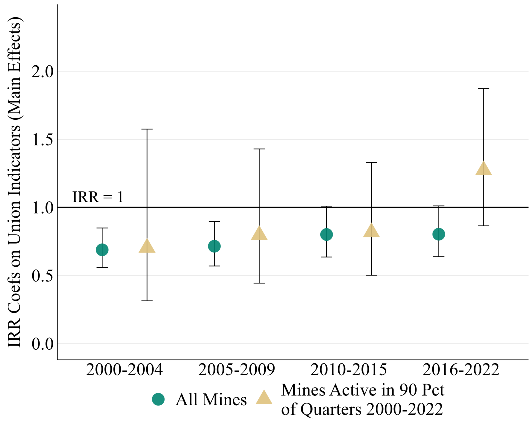
4.4.2 Results

Figure 3 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.[71] 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 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 are indicated by triangles.[72]

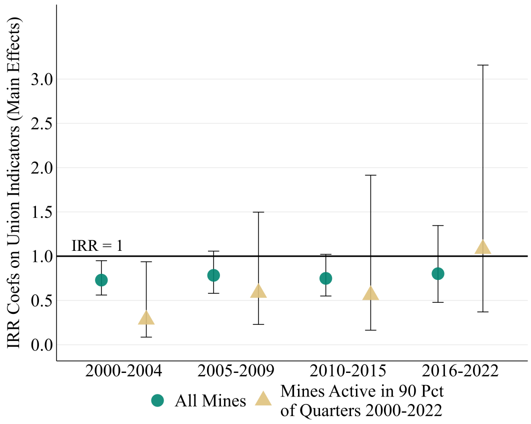
[70]Although the objective here is technically not identification of a union effect. The existence of a union safety premium does not require unions to actually be *causing* safer outcomes. Over-dispersed count data can also be modeled with quasi-Poisson regression models, which weight large and small 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.

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

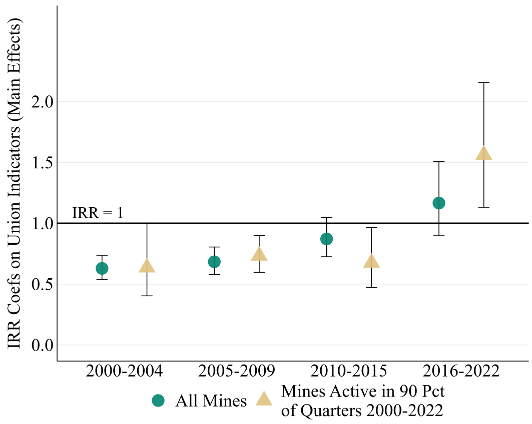
[72]The wide standard errors for the restricted sample are revealing of a loss of statistical power. Tables showing estimates for all covariates and robustness checks where the operation lifetime threshold is varied are in Appendix F. The results are generally robust to the threshold of active quarters used. The story does not



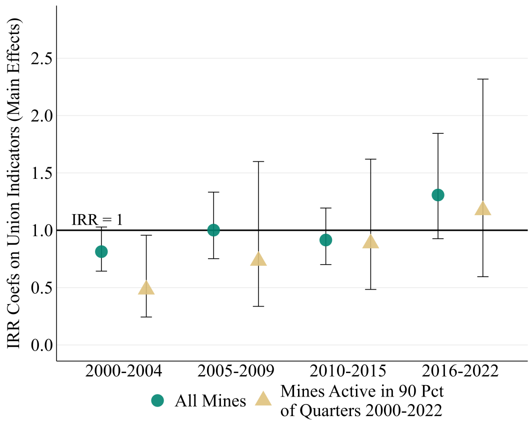
(a) Traumatic Injury Models (Morantz (2013) Specification)



(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 3: Union Safety Premium and Safety Investment Premium Estimates

The trend shown by the green dots in 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 safety premiums estimated for models that also include a union interaction term are plotted in Panel A. These estimates suggest there was never a union safety premium for mines with the longest operation lifetimes in the sample. Panel C shows estimates of the union safety premium from models where the union interaction term is not included. For mines with the longest 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 Panels B and D suggest there was never much of a union safety

change much when one of 70, 75, or 80 percent are used with the original Morantz (2013) specification instead of 90 percent as the active quarter threshold. When the interaction term is dropped, the patterns with other thresholds more closely resembles those in the entire sample but the estimates are less precise.

investment premium at any point from 2000-2022 regardless of the model or operation lifetime sample used.[73] 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).

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.[74] As defined at the beginning of this paper, the union safety premium is simply the average amount by which union mines outperform nonunion mines' safety records. It is a quantity that is distinct from a causal effect of unionization. Thus, my empirical approach is sufficient in the context of this paper.

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 increase their safety investments and 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.

[73]In the language of the theoretical model, $\frac{dp}{dS}$, $\frac{\partial e}{\partial S}$, 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.

[74]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 endogeneously determined, and there is scarcely any variation in union status within mines that can be exploited for identification.

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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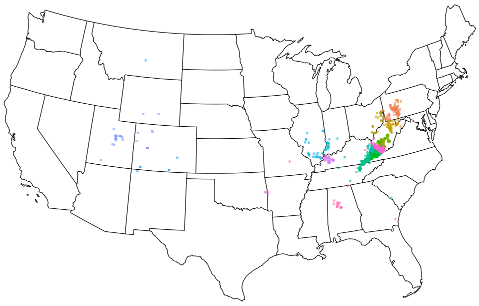
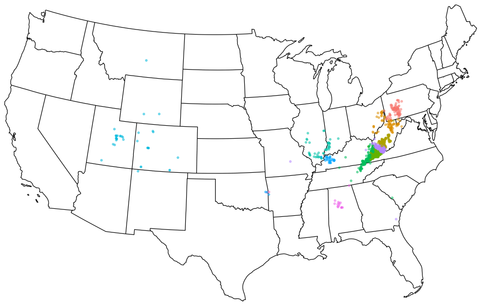
A Data summary statistics and figures



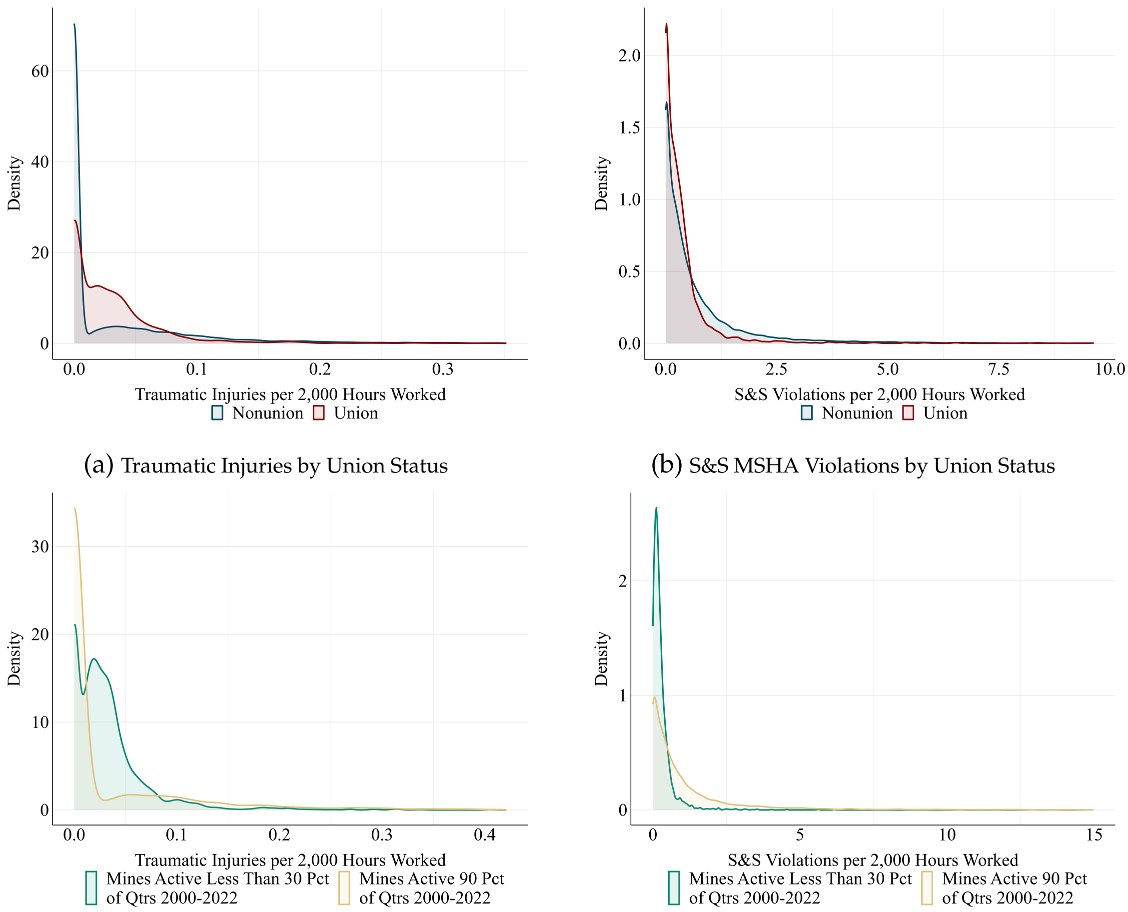
(a) Mines Colored by MSHA Office



(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

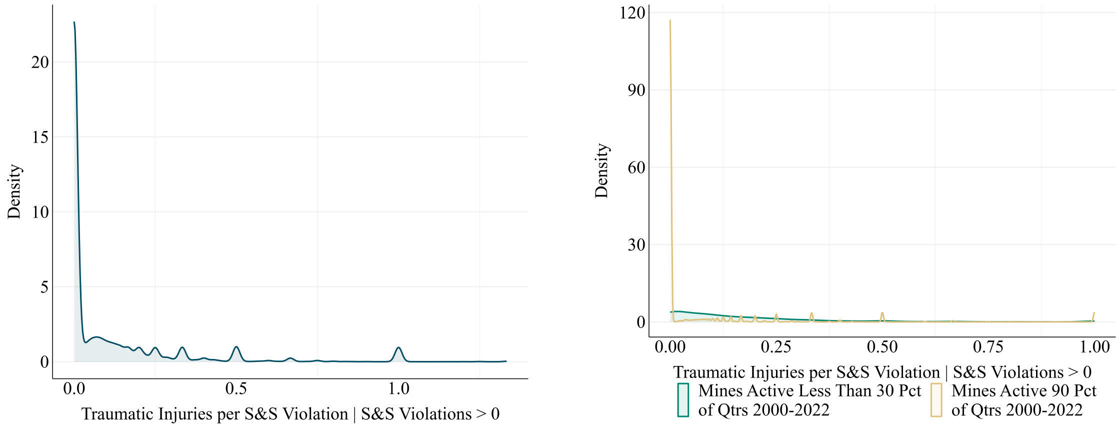
(b) S&S MSHA Violations by Union Status

(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.



(a) Overall

(b) By Operation Lifetime

Figure A3: Distributions of Traumatic Injuries per S&S Violation 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 $\left(\frac{\partial L}{\partial e} = 0\right)$:

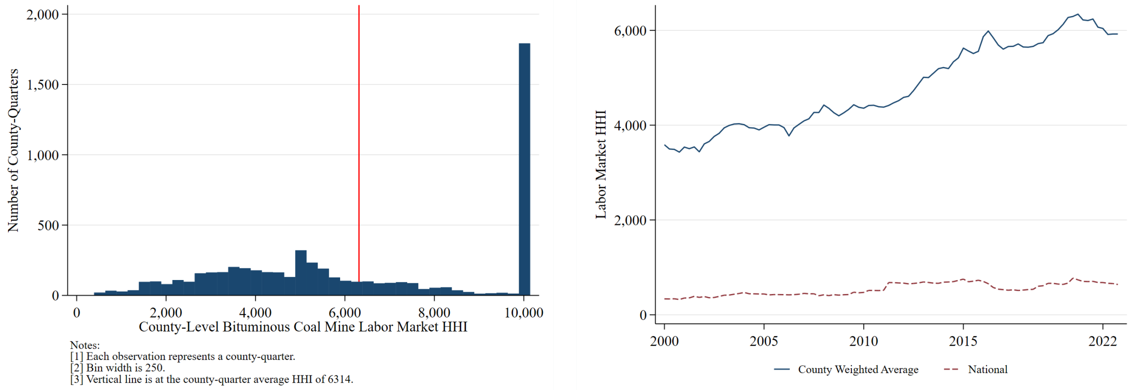
$$
\begin{aligned}
&- U_1' + pU_1' - \frac{\partial p}{\partial e}U_1 - pU_2' + \frac{\partial p}{\partial e}U_2 - (1+i_s)\rho\delta U_3' + (1+i_s)\rho\delta p U_3' - \rho\delta\frac{\partial p}{\partial e}U_3 \\
&- (1+i_s)\rho\delta p U_4' + \rho\delta\frac{\partial p}{\partial e}U_4 - i_s\rho(1-\delta)U_5'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

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

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

C Labor market concentration

Figure A4 gives a rough idea about levels of labor market concentration and associated trends in the underground bituminous coal mining industry. The assumption is that underground bituminous coal mines in a county constitute a labor market. This is likely too restrictive. While workers at these mines almost certainly develop some non-transferrable human capital, construction employers and non-underground mines likely compete for these workers' labor. Thus, the HHI estimates I calculate represent upper bounds on actual labor market concentration.



(a) Local HHI Distribution

(b) Trends in Local and National HHI

Figure A4: Labor Market Concentration

Recall that HHI in market m and year-quarter t is defined as

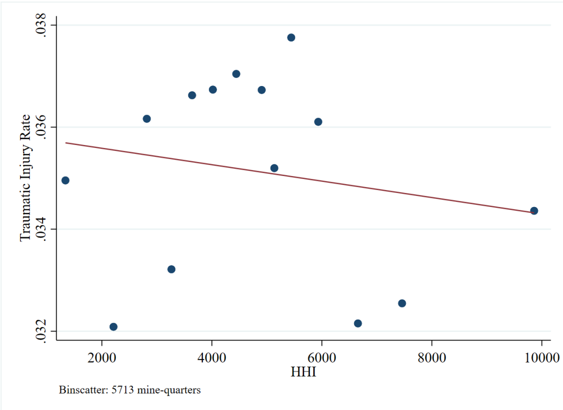
$$\text{HHI}_{m,t} = \sum_{j=1}^{J} s_{j,m,t}^2,$$

where $s_{j,m}$ is the market share of mine controller j in market m, and market share is defined as the share of miners in the market employed by mines owned by controller j.

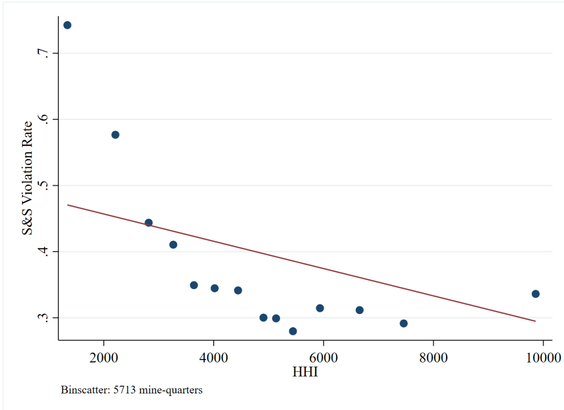
Panel A shows the distribution of of HHIs when the market is defined as a county. The (unweighted) average HHI across all county-quarters used in my analysis is 6,314. This implies that coal miners face highly concentrated labor markets. Even though this measure of market concentration is biased upward, it still aligns with expectations that coal mining, which occurs in very rural areas, would have concentrated labor markets.

Panel B shows that the average coal labor market concentration is likely rising. Rossi-Hansberg, Sarte, and Trachter (2021) find diverging trends in local and national product market concentration. The dashed red line shows the HHI where shares are the national share of labor commanded by each controller company. This trend is increasing over time as well, although this national statistic should not be interpreted as a measure of labor market power per se.

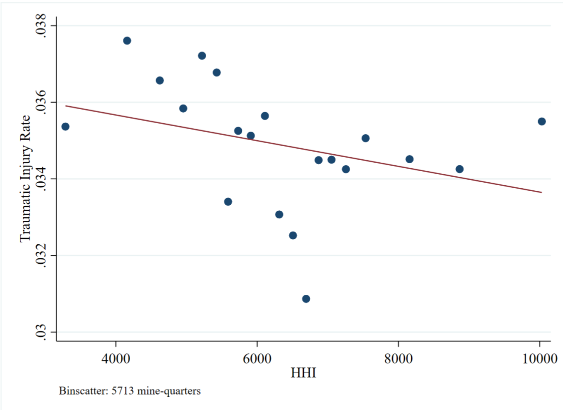
Azar et al. (2022) find that increases in labor market concentration are associated with declines in wages found in job postings. Interestingly, Figure A5 suggests that increases in county-level labor market concentration are associated with *lower* rates of injuries and violations across all mines in the county. This relationship holds up even when conditioning on county and year-quarter fixed effects. Future work may explore this relationship at greater depth. Delabastita and Rubens (2022) find that coal mines colluded to suppress wages around the beginning of the 20th century, but there is not much work on the recent effects (or existence) of coal mine labor market power.



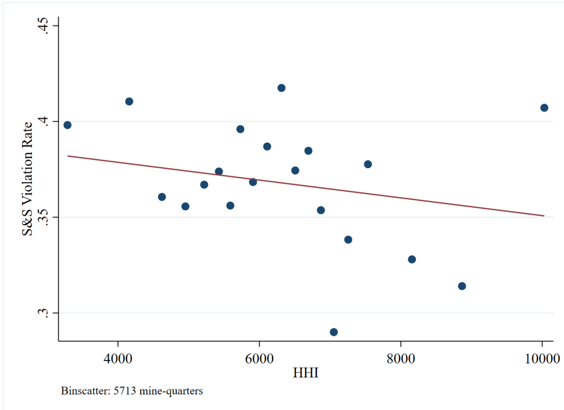
(a) Injuries vs. HHI



(b) Violations vs. HHI



(c) Injuries vs. HHI | County, Year-Quarter FE

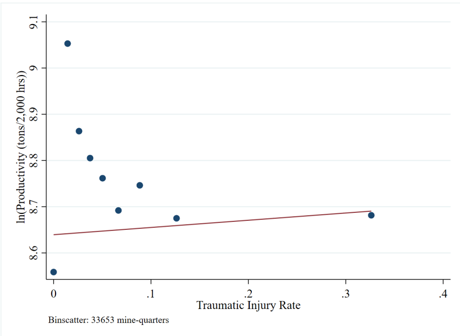


(d) Violations vs. HHI | County, Year-Quarter FE

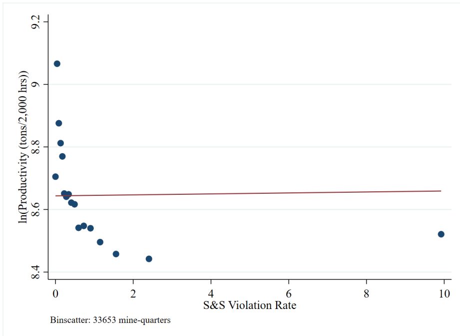
Figure A5: Mine Safety vs. HHI

D Safety and productivity

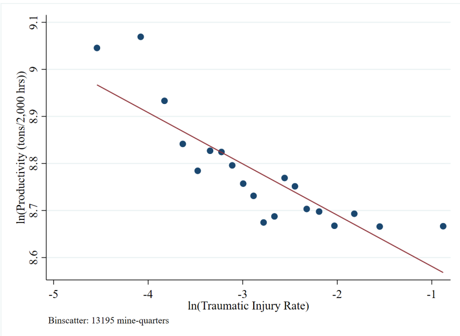
There is a substantial literature concerning the relationship between unions and (labor) productivity (e.g., Doucouliagos and Laroche (2003); Barth, Bryson, and Dale-Olsen (2020); Dosi, Freeman, Pereira, Roventini, and Virgillito (2021)). Estimating the effect of unionization on productivity invites endogeneity and simultaneity bias. Figure A6 shows the instability of the sign of the relationship in the sample I use in this paper. Panels A and B simply show the correlation; Panels C and D drop observations for which the x-variable is 0; Panels E and F show the relationship conditional on mine and year-quarter fixed effects.



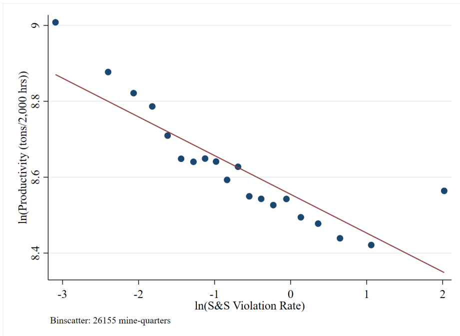
(a) ln(Productivity) vs. Injuries



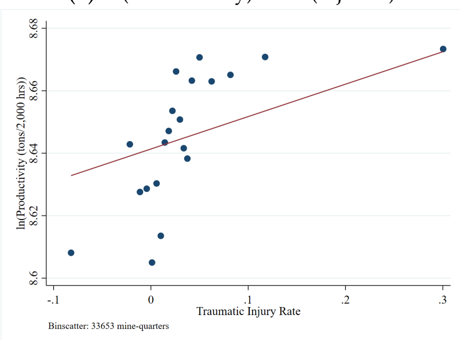
(b) ln(Productivity) vs. Violations



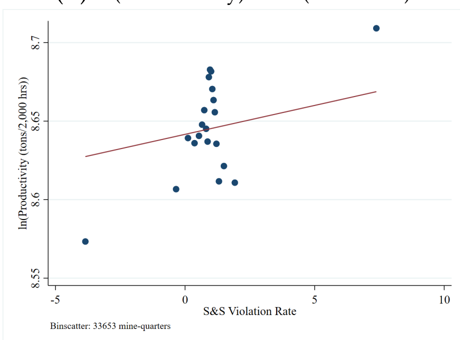
(c) ln(Productivity) vs. ln(Injuries)



(d) ln(Productivity) vs. ln(Violations)



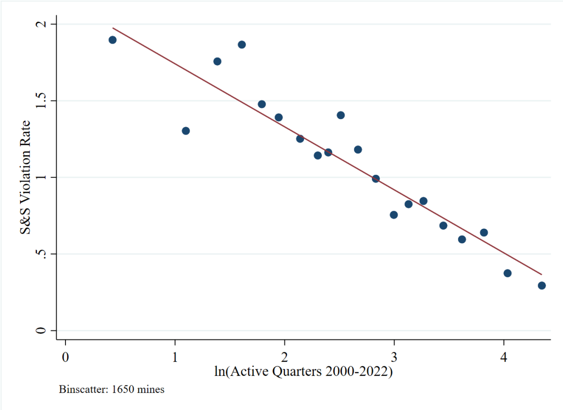
(e) ln(Productivity) vs. Injuries | Mine, Year-Quarter FE



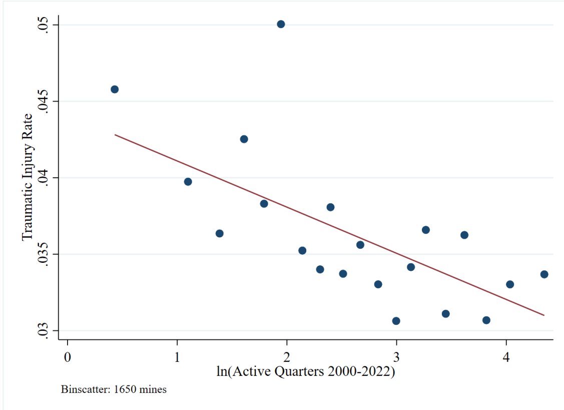
(f) ln(Productivity) vs. Violations | Mine, Year-Quarter FE

Figure A6: Mine Productivity vs. Safety

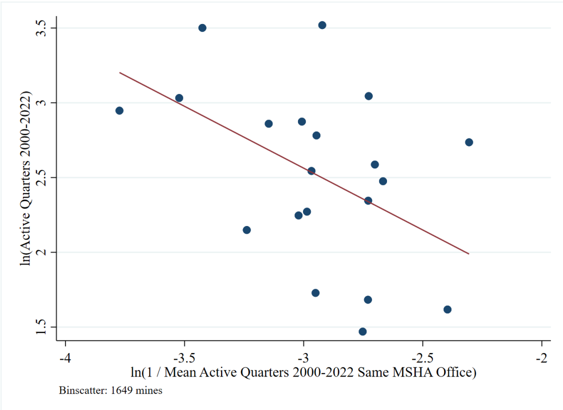
E Safety in firms of different operation lifetimes figures



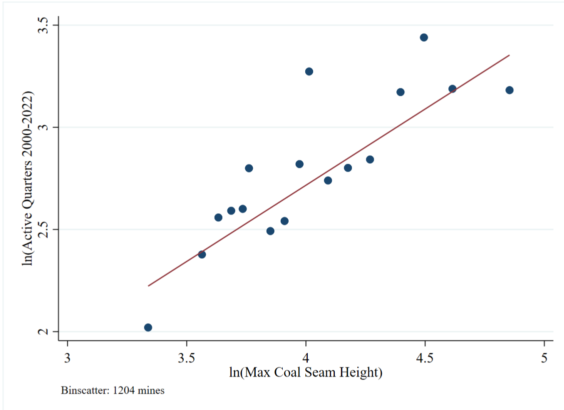
(a) S&S Violation Rate vs. Mine Operation Lifetime



(b) Traumatic Injury Rate vs. Mine Operation Lifetime



(c) MSHA Office Variation IV



(d) Coal Seam Height IV

Figure A7: Operation Lifetime and Mine Safety: Structural Relationships and IV First Stages

F 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.

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

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

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 $\times$ 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.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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

Table A5: Union Safety Premium Expanded Covariate Report for All Mines Active in ≥ 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.

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

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

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

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

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)	(2)	(3)	(4)	(5)	(6)	(7)
	2000-2004	2005-2009	2010-2015	2016-2022	2000-2010	2011-2022	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.

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

Table A10: Union Safety Premium Expanded Covariate Report for All Mines Active in $\geq$ 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.

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

Table A11: Union Safety Premium Expanded Covariate Report for Mines Active in $\geq$ 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.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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

Table A13: Union Safety Premium Expanded Covariate Report for All Mines Active in $\geq$ 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.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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

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 $\times$ 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.

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

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.

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

Table A17: Union Safety Premium Expanded Covariate Report for All Mines Active in $\geq$ 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.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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) 2000-2004	(2) 2005-2009	(3) 2010-2015	(4) 2016-2022	(5) 2000-2010	(6) 2011-2022	(7) 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.

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

Table A19: Union Safety Premium Expanded Covariate Report for Mines Active in $\geq$ 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.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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