John Murray
Rhodes College
Memphis
TN 38112
USA
Javier Silvestre
Estructura e Historia Económica y Economía Pública
University of Zaragoza
c/ Gran Vía 2
Zaragoza 50005
Spain

Small-scale technologies and European coal mine safety, 1850–1900[1]

By JOHN E. MURRAY and JAVIER SILVESTRE*

This article considers new technologies and fatal accident rates in European coal mining from 1850 to 1900. Its contributions are twofold: to recover and emphasize improvements in small-scale mine technologies such as safety lamps and ventilation, and, second, to deny any role at this time for later macroinventions such as electrification and mechanization. We discuss the influence of these safety-improving technologies as well as government regulations on different kinds of fatal accident rates. It is proposed that an important and overlooked source of the reduction in fatalities from certain kinds of accidents was the introduction and diffusion of a variety of safety-related technologies, none of particularly large scale.

> D'ailleurs, il ne songeait guère aux accidents possibles, il s'oublait là maintenant avec les camarades, insoucieux du péril. On vivait dans le grisou, sans même en sentir la pesanteur sur les paupières, l'envoilement de toile d'araignée qu'il laissait aux cils. Parfois quand la flame des lampes pâlissait et bleuissait davantage, on songeait à lui, un mineur mettait la tête contre la veine, pour écouter le petit bruit du gaz, un bruit de bulle d'air bouillonnant à chaque fente.[2]

Here Émile Zola describes one of the great dangers to a coal miner's life: explosive methane, called firedamp (French: *grisou*). In 1885, the year of *Germinal*'s publication, nearly one hundred thousand workers toiled in French coal mines. Of those, 169 died in accidents; 42 of them in firedamp explosions.[3] Thanks to improved mine safety, the number killed in accidents at the turn of the century hardly changed even though two-thirds again as many miners were at risk. Deaths in firedamp explosions had actually fallen by three-fourths. In surely a related development, labour productivity increased over this time, yielding much greater coal output per miner death. Between 1885 and 1903 overall coal production in France nearly doubled, from 18 million to 33 million metric tons, so that the constant number of deaths implied that coal had become half as costly in terms of miners' lives. This article concentrates on sources of that diminishing workplace accident risk throughout the whole of Europe, not just France. In particular, by considering a time without innovations in general purpose technologies or macroinventions, it focuses on the role of small-scale technologies in improving coal mine safety. We propose that they were as important as more closely studied legal and regulatory developments in reducing the risk of death due to accident in European coal production.

From 1850 to 1900 no new general purpose technology appeared in European coal production. Steam power had been introduced earlier in the nineteenth century to drive water pumps and shaft elevators. While pumping technologies and underground transport themselves improved over this time, steam remained the source of motive power throughout the later period. Electrification of mines and mechanized coal cutting were the great advances of the early twentieth century, and so appear too late to enter our story. By elimination, then, improved mine safety must have followed from steady progress in creating and diffusing relatively small technological innovations.

In the absence of new large-scale or general purpose technologies, gross output of European coal over this period increased dramatically. From south Wales to Silesia, the Continent-wide coal supply grew by a factor of seven (table 1). British production, at mid-century by far the greatest in the world, more than quadrupled. Because Germany had just begun to exploit the great Ruhr fields, the relative increase was especially momentous, at more than 20-fold.[4] These increases occurred on the intensive margin, as they were accompanied by greater labour productivity. On the Continent, coal per mine worker increased 25 per cent in Austria, 35 per cent in Belgium, 45 per cent in France, and over 75 per cent in Prussia. At the same time fatal accident risk fell between 50 and 75 per cent everywhere but Prussia (figure 1, table 2). Even in Prussia this rate declined in the 1880s and 1890s. This article casts these falling fatal accident rates against small-scale technological innovation, so as to examine the effect of microinventions on the process of coal production.

It is worth taking a moment to reflect on the timeliness of this research. An historical examination of energy extraction technologies gives perspective on recent controversies. Over the last decade, new methods for withdrawal of carbon-based fuel from the earth have changed energy markets worldwide. Estimated supplies of gas and oil in Britain, Germany, Canada, and the north-eastern US have grown extensively over the last decade thanks to hydraulic fracturing, or fracking. At a time when horizontal drilling and exploitation of previously unreachable deposits is a popular concern due to potential environmental externalities, we might benefit from reviewing the influence of technology on energy extraction in the past, when the energy came from coal rather than oil and gas, and far more labour than capital was at risk underground.

Our primary sources are the later nineteenth-century European mining engineering press. English, German, and French language publications described all manner of new inventions and their performance in a variety of field trials. These reports yielded a rich trove of qualitative data on technological advances as well as new technologies that proved to be dead-ends. Thanks to these publications we can relate detailed descriptions of these new technologies to standard production and accident statistics that appeared in government publications of the time. The importance of these innovations as claimed by inventors and promoters is consistent with econometric tests with a subset of available data.

I

A considerable literature by historians concerns mine safety. Work in this tradition emphasizes government safety regulations. When Bartrip and Burman, for example, illustrated the political process behind policy creation, statistical inference served more to support their main argument than as a mode of inquiry in its own right.[5] Mills followed the growth of British government regulation along lines suggested by MacDonagh's model, but the effects of regulation on accident risks as experienced by miners was a secondary issue.[6] Some studies traced the cultural consequences of high mortality risk, as in the Ruhr region.[7] Others reviewed political struggles over safety measures, as in France.[8] A problem in the link from state regulation to actual practice in Belgium, Leboutte proposed, was the poor education of miners, who failed to understand the value of new safety methods.[9] The literature on mine safety rarely delivers much detail on the technologies employed in mines. Histories of technology have described some of the advances in considerable detail. However, they have typically limited their narrative to the eighteenth and earlier nineteenth centuries, granted very little coverage to Continental Europe, and did not address whether the new technologies had much of an effect on risk levels.[10]

Quantitative historical research has concentrated on labour productivity and production levels. The comprehensive history of British coal mining by Church covered all aspects of miners and mining, but gave production pride of place.[11] The same might be said of Burghardt's work on the Ruhr area, particularly its coverage of mechanization and growth in mine output.[12] Other works consider labour productivity, but primarily in order to form macroeconomic output estimates for national income accounting or other aggregate measures. These pieces examine one country at a time, and generally in the twentieth century.[13] Indeed, histories of European economic growth almost exclusively address coal production at this time, which is only reasonable given its importance.[14] Here we use quantitative methods, but to examine mitigation of risk rather than labour productivity or overall production trends.

A pan-European approach enables insights that might be missed otherwise. To a great degree coal mining was a European project as well as a British, German, French, Belgian, or Austrian one. Coal-winning crossed international borders because the coal itself lay beneath those borders or natural barriers. In a broad geologic sense, much of Continental Europe's coal, from Kent to the Pas-de-Calais to Silesia, forms a single, if discontinuous belt.[15] Fields in the North of France continue through to those in central Belgium. Thanks to the Franco-Prussian War, the Lorraine fields, as a continuation of those in the Saar, present a special case of coal deposits above which national boundaries moved during our time period.[16]

In addition to common deposits the coal producing nations shared a common body of mining knowledge, and did so from an early date. An active mining press disseminated the results of tests and experiments, reports of investigations into disasters, and proposals for the improvement of production and safety. The Revolutionary government in France established *Journal des Mines* in 1795, which was then succeeded by *Annales des Mines* in 1816, which continues to the present. In Germany research on coal and metal mining appeared in *Archiv für Bergbau und Hüttenwesen* between 1818 and 1831, which was then superseded by *Archiv für Mineralogie, Geognosie, Bergbau und Hüttenkunde* until 1854. *Glückauf* (from the miners' greeting, 'Luck up!' or 'Good luck!'), founded in 1865, and the *Berg- und Hüttenmännische Zeitung*, founded in 1842, merged in 1904. In addition, regional publications kept mine and furnace masters up to date on new safety technologies developed elsewhere but which could be applicable locally.[17] In the *Transactions* of the North of England Institute of Mining and Mechanical Engineers, for example, could be found results of field trials of new safety lamps from Britain, Belgium, and Germany.[18]

Flows of information concerning new mining technologies were international, leading to the adoption, or at least consideration, of innovations in fairly short order. As Home Secretary, Lord Palmerston sent two engineers, Joseph Dickinson and Herbert Mackworth, to investigate Continental mines and publish their findings.[19] The French Firedamp Commission charged a mission to study firedamp technologies in Belgium, England, Saxony, Prussia, and Lorraine.[20] German engineers knew of advances in timbering in Belgium, France, and Great Britain from the 1860s onwards.[21] In the early 1870s, the French engineer and geologist Amédée Burat described the most recent Belgian and British innovations in coal extraction and transport. Burat's work circulated widely among French engineers, who also learned from him about German advances in strength of cables.[22] In the 1870s and 1880s work on coal dust explosions, a problem of particular concern at that time, disseminated quickly throughout Europe.[23] In geography, geology, research, and the printed word, efforts to extract coal were surprisingly integrated across Europe.

II

Exploration, mine construction, transport of miners and equipment between surface and work site, the winning of coal from the earth, transport of that coal to the surface, and any processing of the coal at the pithead are each a complex process. To keep our story manageable we concentrate on two interrelated technologies—lighting and ventilation—that experienced rapid and sustained technological advances in the second half of the nineteenth century. To introduce those two technologies we first discuss developments in other mining processes. To begin, mine shafts were sunk deeper over this period. Because coal seams nearer the surface were the first to be exploited, by the later nineteenth century deeper mines were necessary to reach untouched seams. In addition, improvements in pump technology enabled mines to run deeper below the water table. Thus, for example, in Belgium the average depth near Mons reached 361 metres in 1856, and just 10 years later this figure was 437 metres.[24] In France the deepest mine reached 630 metres in 1873, and over 800 metres by 1895.[25]

Greater depths led to the replacement of room-and-pillar mining with longwall mining. Longwall mining first appeared in Britain but then spread throughout Europe during the 1880s and 1890s. In room and pillar the miners worked in the midst of the vein (the room), removing some coal and leaving great blocks of it to hold up the roof (the pillars). The longwall process was often necessary at depths of 300 metres or more. Here many miners worked on a face of about 100 metres' length. The stone, slate, or other scrap materials they removed in the course of winning the coal were packed behind them, forming the gob or goaf that held up the roof. Packing voids in the gob with clay improved air circulation. Longwall mining changed the organization of workers as well. Less skilled workers specialized in packing the gob, and the larger number of workers on the same face led the hewers, carriers, and others less skilled to knit together into cohesive teams. The larger spaces required less powerful means of ventilation, and were less subject to roof and wall collapses.[26]

Another new technique of mine construction developed first in Belgium and then spread to the Ruhr in the late 1880s. This was *firstenbau*, or stoping. Veins of coal in Belgian mines, subject to forces of geological pressure, tended to fold over one another, leading to abundant surface outcroppings and stacks of alternating coal and rock strata that went down relatively deeply. Planar veins tended not to run horizontally, but opened a thin end at the surface and then ran away from the surface diagonally downwards, as near Namur. As a result, Belgian engineers developed methods of starting nearer the surface and working downwards diagonally by steps (underhand stoping) or starting towards the bottom and working upwards (overhead stoping).[27] In the Ruhr this technique was never as common as longwall, but its easy transmission from Belgium when Ruhr mines encountered similar geological formations marks a good example of new technologies crossing borders as needed.[28]

Explosives offered a classic example of substitution of capital for labour in the digging of shafts and roads. Used carefully, explosives could also release coal from strata of rock. By 1835 miners were using gunpowder to blast coal away from the face of the vein. The need to keep sparks from the powder trail apart from ambient firedamp became evident, and so safety fuses for use in mines appeared in Britain in 1831, in France in 1839, and in Prussia in 1844. Later developments in fuses kept the sparks encased in metal or gutta-percha, and research moved on to the questions of better explosives that would not ignite firedamp or coal dust.[29]

Questions of what exactly was the substance that exploded in mines and how explosions occurred drew some of the best scientific minds of the day. Early on, individual scientists worked more or less on their own, but by late in the century nearly every European government with mining interests had established its own research mine and laboratories to investigate problems of explosive materials and gases. A particular puzzle was the possible explosibility of coal dust. Mid-century work in Britain by Faraday and Lyell indicated that coal dust offered the potential to explode on its own, in the absence of firedamp. However, their work failed to penetrate into France, where researchers covered some of the same ground over the next decade. Although firedamp, as Zola observed, was pervasive, it was not the only explosive agent that miners encountered. In 1875 an explosion at a French mine previously thought to be 'dry', or free of firedamp, led investigators to suspect coal dust as the active agent. Unfortunately, not long afterwards Mallard and Le Chatelier erroneously claimed that coal dust could not explode in the absence of firedamp. Thanks to the reputations of Mallard and Le Chatelier, French investigators pursued fruitless paths for decades, until the catastrophe at Courrières on 10 March 1906, where 1,099 miners died.[30] British research in the 1870s and 1880s, also influenced by explosions at dry mines in Wales and Scotland, concluded ambiguously. Not until the Prussian Firedamp Commission conducted rigorous tests at Neunkirchen in the Saarland in the mid-1880s was coal dust assessed properly. As it turned out, some types of coal dust were indeed explosive, but others were not. Testing at Mährisch-Ostrau in Austria found that the varieties of explosible coal dust were more common than previously thought. By the end of the century government laboratories in Woolwich, Gelsenkirchen in Westphalia, and Frameries in Hainaut pursued research on explosives that could be used in gassy mines.[31] Combinations of dynamite with soda crystals, glauber salts, ammonia alum, or ammonium chloride generated explosions that were strong enough to dislodge coal while maintaining a sufficiently low temperature to avoid igniting firedamp.[32]

III

Two closely related and particularly well documented technologies are safety lamps and mine ventilation. Each played a vital role in promoting safety among miners, and simultaneously, if indirectly, enabling greater productivity. National patterns of invention and diffusion emerged in these fields. Some technologies achieved only local use, while others spread throughout Europe. Most invention occurred in Britain and Belgium, and a lesser amount in France. Germany specialized in adapting technologies created elsewhere to its own geological situations.

The first safety lamps appeared in Britain before 1820, and these designs remained in use well into the second half of the century. Safety lamps used various methods to separate the flame in the lamp from ambient air that contained firedamp. As 1868 nearly all the safety lamps in use in Great Britain were variants of these early models: 60 per cent were Davy lamps, 30 per cent Stephenson lamps, and 10 per cent Clanny lamps. Unfortunately, these first-generation lamps were designed to work in still air. Mechanical ventilators that provided reasonably fresh, continuously circulating air forced the obsolescence of first-generation lamps, as they did not remain lighted in wafting air. To relight an extinguished lamp required a miner to walk as many as three miles to a central lamp shop, or take a short cut and attempt to relight the lamp in a potentially gassy space. Soon the Belgian engineer Mathieu-Louis Mueseler created a rather heavy lamp that not only yielded more light but could withstand a slight breeze. Investigation by a government commission led to a mandate in 1851 that required Mueseler lamps in Belgian mines. In France, miners continued to use the Davy lamp almost exclusively into the 1860s, until Jean-Baptiste Marsaut, chief engineer of the Bessèges Coal Company in Gard, created a lamp that would stay lighted in both still and moving air. The Marsaut lamp remained in widespread use in France well into the twentieth century.[33]

Throughout the second half of the century, research on safety lamps, testing, and publication of results proceeded at an intense pace. Groups as varied as the North of England Institute of Mining and Mechanical Engineers, the Belgian government, and the Société de l'Industrie Minérale (a combined trade and scholarly association in France) conducted tests and announced their findings, which in turn influenced regulators. Responding to a Société de l'Industrie Minéral report, the French government issued an *Arrêté Royal* in 1876 that required miners to use bonneted Mueseler lamps with vegetable oil fuel in gassy mines. Combinations of research, development, publicity, and regulation had follow-on consequences for the better. A recent historian attributed much of the decline in Belgian accident fatalities to the widespread use of Mueseler lamps.[34] Testing of new and potentially safer lamps continued apace, led by government-appointed commissions in France (1878–82), Prussia (1880–7), Austria (1885–91), and Saxony (from 1880). These governments built permanent mining safety research stations: France at the School of Mines in Paris; Belgium at Frameries la Bouverie; and Prussia at Bochum and Derne in the Ruhr valley, the Glückhilf-Friedenshoffnung Mine in Silesia, at Neunkirchen in the Saarland, and the Bismarck Mine near Gelsenkirchen. A strength of European coal mining technologies lay in the freedom accorded individual inventors to experiment with different solutions, while subjecting these technologies to public testing by permanent institutions.[35]

Mechanical ventilation of mine shafts and galleries grew from efforts of individual inventors. The mid-nineteenth-century baseline method was simplicity itself: a furnace at the bottom of a shaft. As the hot air rose it drew stale air out of horizontal roads and sent it upwards. By connecting roads and galleries to a downcast shaft that brought fresh air from the surface, mining engineers achieved a continuous flow of air. Swinging doors at road intersections kept flow paths in order so that every room, gallery, and road continuously received its supply of reasonably fresh air. As with many obsolescing technologies, improvements in furnaces allowed them to continue in use throughout our period.[36]

The successor technology to furnaces was the mechanical fan. Rather than a set of rotary blades as in a common window fan, the typical arrangement for a centrifugal fan (French: *ventilateur à force centrifuge*; German: *Schleuderrad*) placed blades orthogonally onto a cylinder, which spun so as to direct the air flow across the axis of the cylinder rather than parallel to it. The earliest machines appeared in Britain and Belgium. The first true fan in Britain, the Brunton, appeared in South Wales in 1851; only one was ever built. A similar fan designed by the great engineer James Nasmyth, however, achieved a degree of popularity in British mines throughout the next decade. Nasmyth intentionally left his design unpatented, which aided its diffusion.[37] The most important design just after mid-century emerged from Belgium, where gassy mines led to research on ventilation. Théophile Guibal (1814–88), a Frenchman who taught at the École des Mines in Hainaut, invented a fan specifically for mining in 1840.[38] Beginning with the basic notion of a centrifugal fan, Guibal added four critical features. He introduced angled fan blades, which he placed in a spiral external casing of his invention, which connected to his unique *évasée* chimney that widened as it rose, and finally he separated the fan and the chimney by a shutter that controlled the quantity of exhaust. While initially the fan could move sufficient air only in mines of moderate depth, eventually it came to displace furnaces even in mines 300 or more metres deep. The Guibal design allowed for some enormous machines, such as the fan at Fünfkirchen (now Pécs), Hungary, which was 22 feet in diameter and 80 inches wide. At Hilda Colliery, South Shields, a Guibal fan in use in the mid-1880s measured 50 feet by 12 feet.[39] By 1876 some 200 Guibal fans had been installed in British mines.[40]

The Guibal fan illustrated how mining technologies diffused internationally. By the late 1870s one estimate placed its numbers as 180 in England, 85 in Belgium, 60 in France, and 30 in Germany.[41] The first Guibal model did not appear in the Lower Rhine district until 1867, but by 1881 in all Prussia there were more Guibal fans than other ventilation technologies combined. Figures 2 and 3 show the number of fans and a variety of measures of work capabilities of those fans in France and in the Ruhr district.[42] In both locations, the numbers and capacities of machines increased dramatically in the 1890s. In France by 1892 all mines but one (Vendin in the relatively new Pas-de-Calais fields) used mechanical ventilation.[43] Around this time a new fan from Britain, the Capell, appeared. It was slow to displace the Guibal, for no obvious technical reason; engineers simply could not believe that the Guibal could be bettered. Capell's fan proved smaller and far more efficient than the Guibal and eventually prevailed. In France, various fans built to conform with the theories of Louis Ser, who was not a mining engineer but a civil engineer who specialized in ventilation of buildings, were becoming more common at the end of the century.[44]

The consequences of all this invention and testing included a fall in the rate of miners' deaths due to firedamp explosions (figure 4). A steady decline marked the British experience, while other countries' rates varied considerably from year to year. What all these fatality rates had in common was a sharp decline to nearly zero during the 1890s. How much of the decline was due to improved lighting, how much to better ventilation, and how much to newer explosives, has been debated for years. MacDonagh proposed that the critical factor was closer mine inspection. Rates of deaths from explosions, which, he claimed, inspectors could prevent, fell, while rates of deaths from falling roofs and walls, which they could not affect, rose.[45] Certainly the statutory scope of government regulation in Britain grew over this time. The Act for the Regulation and Inspection of Mines (1860) and the Coal Mines Regulation Acts (1872 and 1887) expanded the government's ability to enter mines and assess their potential danger. The 1872 law in particular established something resembling modern mine inspections.[46] But regarding firedamp and coal dust explosions, the real drop in the death toll did not occur for two more decades, until the introduction of safer lighting, ventilation, and explosive technologies.[47]

There are other reasons to believe that the effects of non-technological factors might have been quite limited. Jevons did not find political reforms to have had much effect on mine safety, at least until the Coal Mines Acts of 1911 and 1915, later than our period.[48] Attributing falling fatality rates to inspection is problematic in part because the efficacy of mine inspectors anywhere in Europe is not at all clear. MacDonagh quoted an inspector on his visits underground: 'Often I have found men working in great danger for want of their places being propped and sprigged when props and sprags in abundance were lying out of use within a few yards'.[49] Similar tales appear in the German record, as mine inspectors in the Ruhr in 1887 recorded the continuing use of hazardous blasting powder and unsafe lights in gassy mines.[50] Likewise, in France, reports by the Corps des Mines harped on cavalier approaches to safety. Contra Zola, disputes over safety concerns typically did not escalate to the level of strikes.[51] Furthermore, the timing of inspection and accident rate trends seems amiss. Jevons proposed that effective mine inspection really began in 1872, but by that time overall death rates in British mines had already fallen by more than half, and the death rate due to cave-ins had fallen by a third over the previous two decades. In the first few years of the modern inspection era, overall death rates actually rose.

Contemporary writers attributed improvements in the safety record to new technologies rather than union activism, legal regulations, or mine inspections. Abel concluded that the sharp decline of deaths in shaft-related accidents followed from new safety devices. These included guided shaft cages, which were ratchets that would catch on the guiding rail should the central rope break; improvements in winding engines, in particular safety hooks which disengaged the lift in case of overwinding; and generally stronger ropes.[52] Consistent with Jevons, Abel also reported that the 1872 law had only a limited effect on mining safety, and left 'a somewhat high death rate' unchanged. In fact, in contrast to MacDonagh's claims that deaths from cave-ins had risen *as a share* of all mining deaths, Abel observed that the death *rate* of miners due to cave-ins had in fact decreased from 1860 to 1880 (figure 5). The trend here was more or less steadily downwards, while the trend in deaths by explosions was noisy until the later 1890s when it reached nearly zero and stayed there.

Indeed, the decline in cave-in-related deaths was part of a longer-term trend downwards in all mining deaths, in Britain and on the Continent. Where mine inspection laws took effect in certain years, their effect on secular trends in death rates due either to firedamp explosions (figure 4) or to cave-ins (figure 5) was limited. In Belgium, a royal decree of 1884, replacing local and provincial regulations, required mine inspections on a uniform basis throughout the country. This year marked a halfway point between a death rate due to cave-ins of about 10 per 10,000 worker years in the 1860s and that of about five in the 1890s. Much of this decline had already occurred before the law was promulgated.[53] The French case illustrates the disconnect between government inspections of gassy mines and changing death rates due to explosions. Exactly how frequently mines were inspected and firedamp levels were estimated cannot be determined, but it was the case that such regulations became ever more centralized over the last half of the century. By 1870 or so prefectures across several departments established their own regulations, some of which applied to just one mine. A central Ministerial Decree of December 1872 attempted to impose some uniformity on these regulations. The report of the French Fire-Damp Commission in 1881 led to another Ministerial Decree that required mine owners to send safety plans to Paris for approval.[54] Remarkably, this development presaged the highest death rates due to firedamp explosions, *c*. 1890. In Germany relaxed regulation in mid-century may have led to greater risk, or so Trischler argued; however, the effect of such liberalization may also have been mitigated by the 1865 unification of Prussian mining law (the *Allgemeine Berggesetz*). As things turned out, Prussian fatal accident rates indeed rose by two-thirds from mid-century to 1870, perhaps due to liberalization. From this point they stabilized before beginning to decline in the mid-1880s. Thus, if standardization of Prussian mining laws led to safety improvements, it will have done so with a two-decade lag.[55] In general, no conclusive link appears to run from legal regulation to reduced mining fatalities.

There remains the possibility of a macroinvention that almost by itself drove productivity and safety trends. Electrification of mines really awaited the twentieth century. Another important development, mechanization of coal extraction, also occurred after the end of our data series. Although introduced during our period of interest, problems of motive power, maintenance, and reliability prevented coal-cutting machines from diffusing quickly.[56] In turn-of-the-century Britain, some 345 machines helped in the production of about 2 per cent of all coal output.[57] On the Continent, no more than a few dozen British machines appeared in France and Upper Silesia.[58] Tests in Belgium suggested that cutting machines held great potential to displace labour, but remained so expensive that, as one analyst observed, 'We still do not see much use of this machine'.[59] Circular cutting machines did not appear in the Ruhr until 1898.[60] Thus, the downward trends in mortality rates were more likely due to a congeries of small-scale technological advances in a variety of mining fields rather than to one or two major new technologies such as electrification or mechanization.

IV

Data on production, employment, prices, and fatal accidents were collected by the American statistician Carroll Wright from various European government publications. The US government then published the collection as *Coal Mine Labor in Europe* (1905). Wright was a leader in the use of carefully collected statistics to investigate problems of labour reform.[61] Appendix I at the end of this article lists the original sources upon which Wright and his colleagues drew. The general reliability of this source is indicated by our attempts at checking values in both the Wright volume and the documents which it claimed to have used as sources, and in every case the match was exact.[62] While *Coal Mine Labor* provides a wealth of time series for five countries, it offers little information on production technologies. For that we relied on mining manuals and periodicals, which yielded information on ventilation fans and their engines in France and Germany.

Commensurable figures on technological innovation and diffusion are scarce. We were able to find such data only on France and Germany, and only for ventilation technologies. For France, Lamb reported the number of steam engines dedicated to ventilation use from 1880 to 1895.[63] For Germany, Burghardt reported the number of *Ventilatoren* in use in the Ruhr area, which rose from 20 in 1871 to 316 in 1900.[64] We treat the two sets of figures as concerning roughly comparable ventilation technologies, as one engine powered only one fan, and so use them in a single variable called *fans*. In addition, although the German ventilation figures cover the most important coal region, we found detailed accident data only for Prussia as a whole. In the absence of more complete data, then, we treated technology and accident data as representative of all Prussian mines.

To measure risk faced by miners we used the number of deaths in mine accidents per 10,000 above and below ground workers, as reported in *Coal Mine Labor*. We chose death rather than non-fatal accidents due to its fairly (but not completely) unambiguous definition and its universal reporting. Non-fatal accident rates were only available for France. Further, the lack of clarity in defining non-fatal accidents is evident in the French data, where two different sources define injuries differently, and so produce different series. Figures in *Statistique de l'industrie minérale et des appareils à vapeur* were based on injuries that disabled a worker for at least 20 days, while those from *Statistique de l'industrie minère* derive from miners' mutual aid funds and are based on absences of only four days. These sources, however, agree on fatality rates.[65]

The sources defined the death of a mine worker in somewhat different ways. Death of a worker who died underground qualified of course, but no consistent method counted miners who were injured in or above the mine and then died afterwards at home or in hospital. In Belgium, deaths that occurred within one month of the accident were counted as fatal accidents; those occurring longer than one month afterwards were not. Other countries simply did not specify in their statutes how to count deaths. In Britain, by custom the period of eligibility was a year and a day; in France the limit was an unspecified time but generally less than a week.[66]

The definition of 'coal' also requires some elaboration. For Prussia, the coal was hard coal, also called *charbon* or *Steinkohle*. The records do not generally distinguish between anthracite and bituminous, as only Britain and France produced any anthracite, and small amounts at that. The German, but not the French, data distinguished between coal and lignite (German: *Braunkohle*) for all years. Lignite consists of less carbon and more water and has a lower calorific value than black coal. It was also mined differently, in open pits or with shallow, often adit, shafts. As a result, in the German data we separated lignite from coal data, and used hard coal data only. However, the available French records of production and employment failed to distinguish between coal and lignite during 1873 to 1878. This is probably not a great problem, as lignite production was only 3 to 4 per cent of hard coal production in the years before and after the mid-1870s. For this reason, we report combined coal and lignite production for France for all years.

In addition to raw quantity of coal, we include its price as another control variable. The 'price' of Continental coal is an approximation; original documents reported the value and the quantity of annual production, and the American investigators simply divided value by quantity to get the price per ton. Whether that price was at the pithead or as paid by the final consumer was not reported.[67]

Finally we propose to test the potential effectiveness of non-technological forces. During the years of available data each country experienced a change in the laws that regulated coal mining. In France, a law of March 1884 liberalized conditions for organizing mine workers' unions, which led to a rapid increase in membership. In Germany, a June 1892 amendment to the 1865 general mining act required closer inspections of mines.[68] In each case we use a variable set equal to one for the country after the legislation took effect (that is, the year after its passage) and zero for previous years. Table 3 relates the mean values of all variables used, pooled and separated by country.

V

Our econometric modelling is intentionally simple. We test whether new technologies as well as improved legal supervision made mines safer, but in particular ways. Ventilation technologies should have decreased the risk of death due to firedamp or coal dust explosions, but should have had little effect on cave-ins. Inspections by fellow miners in Germany and newly empowered union officials in France, contra MacDonagh, should have been able visually to detect improperly timbered galleries, roads, and shafts, and so should have reduced the risk of death due to structural collapse. Inspectors may also have acted on questions of ventilation in gassy mines, but given the questions raised in *Germinal* of mismatched incentives behind miners doing their own timbering, we might propose that inspectors and union stewards would have been more effective at reducing the risk of death due to ceiling and wall collapses. Im, Pesaran, and Shin tested for unit roots, with intercept and time trend, and rejected the null of unit roots at the 1 per cent level of confidence.[69]

The results appear in tables 4 and 5. The first set of regressions uses levels of each variable and the second set uses first differences to mitigate problems of unobserved heterogeneity. Further, to reduce problems of endogeneity in which fans might have been installed after fatal accidents, we introduce lagged values of the numbers of fans. The results are reported for one-way fixed effects models but are robust to estimation by one-way random effects models, with and without intercepts. The results are broadly consistent with our proposals regarding differential effectiveness of technologies and regulations. Numbers of fans and differences in these numbers (that is, new installations of fans) were significantly associated with fewer deaths due to firedamp explosions. The effects of regulation varied by country and may be, in the French case, contaminated by endogeneity in the levels regression. The German case is the more straightforward. In differences, the revision of the mining code in 1894 was associated with fewer deaths of all kinds. In levels the German coefficients were exactly what we expected: legal revision was associated with fewer wall and ceiling collapses but had no other effect on accidental death rates. The French case, again, is more ambiguous. In France the shift in legal regulation was associated with fewer deaths by structural collapse in model a.3, and with fewer overall deaths in the difference regression d.1. However, the level regressions b indicate perverse results, perhaps because the new law enabled unions to form earliest in the most dangerous mines, as Loubère suggested.[70] Overall, we can say that the statistical results supported our most important claims concerning technology: the installation of fans reduced deaths due to firedamp explosions. In Germany the statistical results were consistent with our hypotheses concerning regulation, and the regulation results for France were mixed.

These findings also indicate a positive relationship between production levels (and differences) and fatal accident risk, which may be related to categorization of labourers. German mines hired two classes of mineworkers, those continuously employed (*ständige*) and those employed only temporarily (*unständige*). As of the beginning of our period, the share of miners in Prussian mines who were *unständige* was increasing. The *unständige* miners had their own job classifications and ladders, and could not reach permanent status until they had spent some six to eight years as temporary workers. When work slowed, the *unständige* miners were dismissed first, and so they tended to be less experienced than *ständige* miners. When mines increased production, they recalled the temporarily employed miners to enter the pits. Lacking the continuous experience of the *ständige* men, the fresh miners were more likely to make errors that led to fatal results. The same division, incidentally, also appeared in Austrian workforces.[71]

VI

We propose that in European coal production new safety technologies reduced fatal accident risk. Over this period government action in workplace safety included factory and mine inspection laws that aimed to prod mine owners into making collieries safer under threat of legal sanctions.[72] However, by a variety of accounts, government regulation was easier to promulgate than to execute. Geographically, for example, the German Empire limited enforcement of its 1869 Commercial Code to Prussia proper, despite expansion of inspection powers in Saxony, Bavaria, and Alsace and Lorraine.[73] Indeed, supplemental German mining laws of 1892 appeared in the midst of a prolonged fall in fatality rates. The effect of new laws, then, might have been to increase the rate of decline, but could not have been to initiate it. A similar pattern appeared in France, where a relatively weak safety law of 1890 called for experienced miners to conduct inspections.[74] The law was inspired by a series of disasters in the Loire basin, but its enactment occurred after the death rate, according to trend, had already dropped by some three-fourths, and the years that followed showed a slight increase in the fatal accident rate.[75] The British case also indicated little direct effect of legislation on actual safety conditions. Mills, for example, concluded that the much celebrated 1872 Coal Mines Regulation Act 'failed to produce any significant decline in accident mortality'.[76] Regarding a later period, McIvor and Johnston described 'a massive gulf between what [the Coal Mines Acts] legislated … and actual workplace practice'.[77]

One aspect of exposure to risk that we cannot address is work intensity. It is possible that improvements in safety reflected changes in time spent underground, or perhaps the decreasing willingness of miners to engage in risky practices such as relighting extinguished lamps *in situ*, or miners may have taken more care in setting explosive charges.[78] We lack sources to address this question for France and Germany. In quantitative terms, late in our period days worked per year increased in both Belgium and Great Britain, a trend which would have increased risk exposure during a typical work-year.[79] One change in incentives imposed from outside the pits came from accident insurance. Those systems with experience-rated premiums provided incentives to reduce workplace dangers.[80] Laws that expanded coverage in mining appeared toward the end of the nineteenth century.[81] As unions grew in membership, they recognized the importance of mine safety and led strikes at particularly dangerous collieries.[82] However, it appears that such activities occurred long after the onset of the trends in fatal accident risk considered here. The most direct source of safer coal mines was a series of relatively small-scale technologies that until now have largely been overlooked.

Date submitted *5 October 2012*
Revised version submitted *4 June 2014*
Accepted *10 June 2014*

Footnote references

A. H., 'Nécrologie', *Revue universelle des mines de la métallurgie*, 3rd ser., 4 (1888), pp. i–iii.

Abel, F., *Mining accidents and their prevention* (New York, 1889).

Adams, W. W., 'A miner's yearly and daily output of coal', *Monthly Labor Review*, 11 (1920), pp. 522–30.

Anon., 'Statuten der Knappschaft und Knappschaftskasse', *Österreichische Zeitschrift für Berg- und Hüttenwesen*, 7 (1859), pp. 125–33.

Anon., 'The "Capell" patent double-power fan', *Machinery Market* (1 Nov. 1884), p. 273.

Anon., 'Accidents in mines: I. Method of working and ventilation', *Engineering News*, 16 (1886), p. 204–6.

Anon., 'Progress in mining: abstracts from the proceedings of the mining societies and journals of Europe and America', *Colliery Engineer and Metal Miner*, 17 (1896–7), pp. 409–11.

Arnould, G., *Bassin houiller du Couchant de Mons: Mémoire historique et descriptif* (Mons, 1877).

Banken, R., *Die Industrialisierung der Saarregion 1815–1914*, I: *Die Frühindustrialisierung 1810-1850* (Stuttgart, 2003).

Banken, R., *Die Industrialisierung der Saarregion 1815–1914*, II: *Take-Off-Phase und Hochindustrialisierung 1850–1914* (Stuttgart, 2003).

Bartrip, P. W. J. and Burman, S. B., *The wounded soldiers of industry: industrial compensation policy, 1833–1897* (Oxford, 1983).

Bedson, P. P. and Belinfante, L. L., trans., 'Report of the Prussian Fire-Damp Commission', *Transactions of the Federated Institution of Mining Engineers*, 3 (1891–2), pp. 1105–50; 4 (1892–3), pp. 631–80; 5 (1892–3), pp. 500–54.

Boyer, J., *Unfallversicherung und Unternehmer im Bergbau: Die Knappschafts-Berufgenossenschaft, 1885–1945* (Munich, 1995).

Burat, A., *Les houillères en 1872* (Paris, 1872).

Burghardt, U., *Die Mechanisierung des Ruhrbergbaus, 1890–1930* (Munich, 1995).

Burhop, C., 'The level of labour productivity in German mining, crafts, and industry in 1913: evidence from output data', *European Review of Economic History*, 12 (2008), pp. 201–19.

Capell, G. M., 'Observations on fans of different types working on the same upcast shaft', *Transactions of the North of England Institute of Mining and Mechanical Engineers*, 42 (1892–3), pp. 57–61.

Church, R., *The history of the British coal industry*, 3: *1830–1913, Victorian pre-eminence* (Oxford, 1986).

Clapham, J. H., *The economic development of France and Germany, 1815–1914* (Cambridge, 1921).

Conus, M.-F. and Escudier, J.-L., 'Les transformations d'une mesure: La statistique des accidents dans les mines de charbon en France, 1833–1988', *Histoire et Mesure*, XII (1997), pp. 37–68.

Denoël, L., 'Les moyens de production et l'effet utile de l'ouvrier dans les houillères belges', *Commission d'enquête sur la durée du travail dans les mines de houille* (Brussels, 1909).

Dickinson, J., 'On the Marsaut safety lamp', *Transactions of the Manchester Geological Society*, 17 (1884), pp. 185–95.

Dickinson, J., 'The progress of mining and geology', *Transactions of the Manchester Geological Society*, 19 (1888), pp. 272–318.

Galloway, R. L., *A history of coal mining in Great Britain* (1882; repr. Newton Abbot, 1969).

Greasley, D., 'The diffusion of machine cutting in the British coal industry, 1902–1938', *Explorations in Economic History*, 19 (1982), pp. 246–68.

Greasley, D., 'Fifty years of coal-mining productivity: the record of the British coal industry before 1939', *Journal of Economic History*, 50 (1990), pp. 877–902.

Guinnane, T. W. and Streb, J., 'Incentives that saved lives: government regulation of accident insurance associations in Germany, 1884–1914', Economic Growth Center, Yale University, working paper 1013 (2012).

Guttmann, O., *The manufacture of explosives*, vol. 2 (1895).

Hair, P. E. H., 'Mortality from violence in British coal-mines, 1800–50', *Economic History Review*, 2nd ser., XXI (1968), pp. 545–61.

Hardwick, F. W. and O'Shea, L. T., 'Notes on the history of the safety-lamp', *Transactions of the Institution of Mining Engineers*, 51 (1915), pp. 548–724.

Hoffman, F. L., 'Problems of labor and life in anthracite coal mining: part IV, accidents', *Engineering and Mining Journal*, 74 (13 Dec. 1902), pp. 783–84.

Im, K. S., Pesaran, M. H., and Shin, Y., 'Testing for unit roots in heterogeneous panels', *Journal of Econometrics*, 115 (2003), pp. 53–74.

Jevons, H. S., *The British coal trade* (1915).

Jopp, T. A., *Insurance, fund size, and concentration: Prussian miners' Knappschaften in the nineteenth- and early twentieth-centuries and their quest for optimal scale* (Berlin, 2013).

Keller, O., 'Statistique des caisses de secours pour les mineurs et des autres institutions de prévoyance avant fonctionné sur les houillères en 1882', *Annales des Mines*, 8th ser., 6 (1884), pp. 321–79.

Kirby, P., 'Attendance and work effort in the Great Northern Coalfield, 1775–1864', *Economic History Review*, 65 (2012), pp. 961–83.

Lamb, G. J., 'Coal mining in France, 1873 to 1895' (unpub. Ph.D. thesis, Univ. of Illinois, 1976).

Leboutte, R., 'Mortalité par accident dans les mines de charbon en Belgique aux XIX[e]–XX[e] siècles', *Revue du Nord*, 73 (1991), pp. 703–36.

Leiby, J., *Carroll Wright and labor reform: the origin of labor statistics* (Cambridge, Mass., 1960).

Loubère, L., 'Coal miners, strikes and politics in the Lower Languedoc, 1880–1914', *Journal of Social History*, 2 (1968), pp. 25–50.

Lucassen, J., 'The other proletarians: seasonal labourers, mercenaries and miners', *International Review of Social History*, 39, S2 (1994), pp. 171–93.

MacDonagh, O., 'Coal mines regulation: the first decade, 1842–1852', in R. Robson, ed., *Ideas and institutions in Victorian Britain: essays in honor of George Kitson Clark* (1967), pp. 58–86.

McIvor, A. and Johnston, R., *Miners' lung: a history of dust disease in British coal mining* (Aldershot, 2007).

Mallard, E. and Le Chatelier, H. L., 'Du rôle des poussières de houille dans les accidents de mines', *Annales Des Mines*, 1 (1882), pp. 5–98.

Marshall, A., *Explosives: their manufacture, properties, tests, and history* (Philadelphia, Pa., 1915).

Martin, M., 'Allgegenwärtiger Tod: Arbeitsbedingungen und Mortalität im Ruhr-Bergbau bis zum Ersten Weltkrieg', *Historical Social Research*, 34 (2009), pp. 154–73.

Mills, C., *Regulating health and safety in the British mining industries, 1800–1914* (Farnham, 2010).

Mitchell, B. R., *International historical statistics: Europe, 1750–1988* (1992).

Murray, J. E., 'Social insurance claims as morbidity estimates: sickness or absence?', *Social History of Medicine*, 16 (2003), pp. 225–45.

Murray, J. E. and Nilsson, L., 'Accident risk compensation in late imperial Austria: wage differentials and social insurance', *Explorations in Economic History*, 44 (2007), pp. 568–87.

Nasmyth, J., *James Nasmyth, engineer: an autobiography* (1883).

Neville, R. G., 'The Courrières colliery disaster, 1906', *Journal of Contemporary History*, 13 (1978), pp. 33–52.

Pernolet, A. and Aguillon, L.-C.-M., *Exploitation et réglementation des mines à grisou en Belgique, en Angleterre, et en Allemagne: Rapport de mission fait à la commission chargée de l'etude des moyens propres à prévenir les explosions de grisou dans les houillères*, I: *Belgique* (Paris, 1881).

Pounds, N. J. G. and Parker, W. N., *Coal and steel in western Europe: the influence of resources and techniques on production* (1957).

Reid, D., 'The role of mine safety in the development of working-class consciousness and organization: the case of the Aubin coal basin, 1867–1914', *French Historical Studies*, 12 (1981), pp. 98–119.

Rice, G. S., *The explosibility of coal dust*, *US Geological Survey Bulletin 425* (Washington, DC, 1910).

Ser, L., *Essai d'une théorie des ventilateurs á force centrifuge: Détermination de leurs formes et de leurs dimensions* (Paris, 1878).

Silvestre, J., 'Workplace accidents and early safety policies in Spain, 1900–1932', *Social History of Medicine*, 21 (2008), pp. 67–86.

Singer, C., Holmyard, E. J., Hall, A. R., and Williams, T. I., eds., *A history of technology*, IV: *The industrial revolution, c. 1750 to c. 1850* (New York, 1958).

Tonneau, E., *De l'exploitation de la houille en Belgique* (Liége, 1860).

Treble, J. G., 'Productivity and effort: the labor-supply decisions of late Victorian coalminers', *Journal of Economic History*, 61 (2001), pp. 414–38.

Trischler, H., 'Arbeitsunfälle und Berufskrankheiten im Bergbau 1851 bis 1945: Bergbehördliche Sozialpolitik im Spannungsfeld von Sicherheit und Produktionsinteressen', *Archiv für Sozialgeschichte*, 28 (1988), pp. 111–51.

Verein für die Bergbaulichen Interessen im Oberbergamtsbezirk Dortmund, *Die Entwickelung des Niederrheinisch-westfälischen Steinkohlen-Bergbaues in der zweiten Hälfte des 19. Jahrhunderts*, vol. VI (Berlin, 1903).

Wabner, R., *Die Bewetterung der Bergwerke* (Leipzig, 1902).

Walker, S. F., *Coal cutting by machinery in the United Kingdom* (1902).

Wood, N., 'On safety lamps for lighting coal mines', *Transactions of the North of England Institute for Mining and Mechanical Engineers*, 1 (1852/3), pp. 301–22.

Wrigley, E. A., *Industrial growth and population change: a regional study of the coalfield areas of north-west Europe in the later nineteenth century* (Cambridge, 2006).

Zola, E., *Germinal*, C. Becker, ed. (Paris, 2000).

Official publications

Annales des mines de Belgique, vols. VI–IX (Brussels, 1901–4).

Annales des travaux publics, vol. XL (*Développement de l'industrie houillère en Belgique*) (Brussels, 1883).

Extraits des annales des mines de Belgique, vols. I–V (Brussels, 1896–1900).

Mines and Quarries: General Reports and Statistics, 1900–1903 (1901–4).

Reports from Committees (P.P. 1852, V).

Résumé des travaux statistiques de l'administration des mines (Paris, 1853–72).

Statistical Abstract for the United Kingdom, no. 12 (1865).

Statistical Abstract for the United Kingdom, no. 21 (1874).

Statistique de l'industrie minérale et des appareils à vapeur en France et en Algérie (Paris, 1873–1903).

Statistique des accidents survenus dans les charbonnages de 1831 à 1888 (Brussels, 1889).

Statistique des accidents survenus dans les charbonnages de 1831 à 1888 (*Extraits des annals des travaux publics*, vol. XLVII) (Brussels, 1890).

Statistique des mines, minières, carrières, etc. (*Extraits des annals des travaux publics*, vols. XLI–LII) (Brussels, 1884–96).

Statistisches Jahrbuch des K. K. Ackerbau Ministeriums, 1875–1903 (Vienna, 1876–1904).

Wright, C. D., *Coal Mine Labor in Europe, Twelfth Special Report of the Commissioner of Labor* (Washington, DC, 1905).

Zeitschrift für das Berg-, Hütten- und Salinenwesen im Preussischen Staate, vols. I–LII (Berlin, 1853–1904).

Zeitschrift für das Berg-, Hütten- und Salinenwesen im Preussischen Staate, Statistischer Theil, Zusammenstellung, Von Althaus, 1852–61 (Berlin, 1853–62).

Figure 1. Trends in accident fatality rates per 10,000 worker years, European coal mines

Source: See app. I.

Figure 2. Fan introduction and diffusion through the Ruhr district

Source: Burghardt, *Mechaniesierung*, p. 380.

Figure 3. Steam power for mine ventilation fans in France

Sources: Lamb, 'Coal mining', p. 186, and later issues of *Statistique de l'industrie minérale*.

Figure 4. Death rate per 10,000 worker years due to firedamp or coal dust explosions

Source: Wright, *Coal Mine Labor*.

Figure 5. Death rate per 10,000 worker years due to roof collapses, falling earth, cave-ins, and so on

Source: Wright, *Coal Mine Labor*.

Table 1. Output of hard coal in Europe

	1850	*1860*	*1870*	*1880*	*1890*	*1900*
Austria	665[a]	1,706	3,759	5,890	8,931	10,993
	0.98	1.47	2.22	2.45	2.80	2.72
Belgium	5,821	9,611	13,697	16,867	20,366	23,463
	7.34	8.02	7.66	6.85	6.29	5.39
France[b]	4,434	8,304	13,330	19,362	26,083	33,404
	5.47	7.00	7.60	7.84	8.01	7.83
Germany	5,100	12,348	26,398	46,974	70,238	109,290
	6.70	10.63	15.66	19.18	22.13	25.42
Great Britain	50,200	81,327	112,203	149,327	184,528	228,794
	79.31	72.14	65.78	61.55	57.95	53.69
Five main producers (%)	99.80	99.26	98.92	97.87	97.18	95.04
Europe as a whole	63,296	112,734	170,573	242,611	318,426	426,139
	100	100	100	100	100	100

Notes: a 1851.
b Hard coal and lignite combined.
Upper no. is production in millions of metric tons. Lower no. is share (%) of European production.
Source: Mitchell, *International historical statistics*.

Table 2. Years of available data

		First year	*Last year*
Austria	Years	1875	1903
	Productivity	142.5	179.5
	Fatal accidents	35.1	7.7
Belgium	Years	1851	1902
	Productivity	125.9	169.6
	Fatal accidents	21.8	10.7
France	Years	1853	1901
	Productivity	144.4	208.8
	Fatal accidents	38.7	10.2
Prussia	Years	1852	1903
	Productivity	143.2	253.1
	Fatal accidents	16.4	19.2
Great Britain	Years	1854	1903
	Productivity	273.9	273.5
	Fatal accidents	41.7	12.0

Note: Productivity = tons of coal per worker. Fatal accidents = deaths per 10,000 workers.
Source: Wright, *Coal Mine Labor*.

Table 3. Mean values and standard deviations of regression variables

	France	*Germany*	*Total*
Total death rate (per 10,000 worker years)	16.43 (5.78)	28.27 (4.09)	24.15 (7.38)
Death rate: explosions of firedamp	4.19 (5.33)	3.61 (2.44)	3.81 (3.66)
Death rate: collapses of walls or ceilings	4.95 (1.19)	10.36 (1.34)	8.48 (3.90)
Years of data	1880–99	1867–1900	1867–1900
Price of coal (US dollars per metric ton)	2.40 (0.32)	1.55 (0.40)	1.85 (0.55)
Quantity of coal (millions of metric tons)	22.45 (3.08)	55.62 (20.75)	44.08 (23.15)
No. of ventilation fan engines	188.38 (42.19)	138.03 (89.71)	155.54 (79.80)
Years of closer regulation	1885–99	1893–1900	
N	20	34	54

Table 4. Panel regressions in levels, dependent variable = deaths per 10,000 worker years

	a.1	*a.2*	*a.3*	*b.1*	*b.2*	*b.3*
Dependent variable →	*All deaths*	*Firedamp explosions*	*Ceiling, wall collapses*	*All deaths*	*Firedamp explosions*	*Ceiling, wall collapses*
Constant	28.65*** (3.23)	–0.31 (3.03)	12.97*** (0.59)	15.68*** (0.10)	–8.60*** (2.54)	10.40*** (0.29)
Fans year *t*	–0.13 (0.11)	–0.15* (0.08)	0.01 (0.01)	–0.06 (0.08)	–0.13*** (0.04)	0.01 (0.02)
Fans year *t-1*				–0.20*** (0.03)	–0.08*** (0.01)	–0.03 (0.02)
Prussia	–5.19 (4.44)	5.25* (2.99)	–3.60*** (0.51)	20.60*** (1.55)	22.24*** (3.52)	1.90*** (0.60)
Prussia*1893	1.03 (2.11)	–0.49 (1.48)	–0.54* (0.28)	1.40 (0.86)	–0.72 (0.55)	–0.26*** (0.004)
France*1885	–0.60 (1.99)	–0.58 (1.57)	–0.66*** (0.24)	5.71*** (1.19)	4.18*** (0.63)	1.06*** (0.08)
Price	0.24 (1.69)	1.38 (1.72)	–1.33*** (0.39)	–1.93*** (0.02)	–0.36 (0.58)	–1.92*** (0.01)
Quantity of coal/1M	0.89*** (0.23)	0.46** (0.20)	0.29*** (0.04)	0.67*** (0.03)	0.46*** (0.04)	0.15*** (0.006)
Year	1.01 (1.00)	1.46** (0.72)	–0.17 (0.11)	0.77 (0.55)	1.13** (0.43)	–0.29*** (0.03)
R^2	0.69	0.30	0.89	0.79	0.45	0.91
N		54			52	

Notes: Heteroskedastic consistent standard errors. * = significant at 0.10 level; ** at 0.05 level; *** at 0.01 level.
Sources: See app. I.

Table 5. Panel regressions in differences, dependent variable = deaths per 10,000 worker years

	c.1	*c.2*	*c.3*	*d.1*	*d.2*	*d.3*
Dependent variable →	*All deaths*[a]	*Firedamp explosions*[a]	*Ceiling, wall collapses*[a]	*All deaths*[a]	*Firedamp explosions*[a]	*Ceiling, wall collapses*[a]
Constant	1.22*** (0.31)	–0.20 (0.62)	–0.53*** (0.14)	–0.75*** (0.15)	0.94* (0.53)	–0.61** (0.26)
Fans year *t*[a]	–0.10 (0.10)	–0.08* (0.04)	0.02 (0.02)	–0.01 (0.09)	–0.08* (0.04)	0.02 (0.02)
Fans year *t-1*[a]				–0.08*** (0.006)	0.01*** (0.0006)	–0.003 (0.002)
Prussia	1.95 (1.95)	0.95 (1.41)	0.39 (0.52)	3.39* (1.90)	1.37 (1.52)	0.60 (0.59)
Prussia*1893	–1.29** (0.59)	–1.40*** (0.48)	–0.53*** (0.10)	–1.90*** (0.04)	–0.95*** (0.24)	–0.59*** (0.15)
France*1885	0.16 (0.32)	–0.81 (0.59)	–0.02 (0.12)	–2.31*** (0.16)	–0.73 (0.50)	–0.24 (0.26)
Price[a]	0.89 (1.90)	0.60 (2.06)	–1.60*** (0.40)	–2.46*** (0.78)	2.05 (1.31)	–1.79*** (0.66)
Quantity of coal/1M[a]	1.22*** (0.28)	0.45*** (0.04)	0.28*** (0.02)	1.03*** (0.21)	0.56*** (0.14)	0.29*** (0.01)
Year	–0.24*** (0.05)	0.004 (0.03)	–0.02** (0.01)	–0.05*** (0.02)	–0.09*** (0.03)	–0.02*** (0.002)
R^2	0.15	0.07	0.12	0.31	0.10	0.12
N		52			50	

Notes: a Variable in differences.
Heteroskedastic consistent standard errors. * = significant at 0.10 level; ** at 0.05 level; *** at 0.01 level. Method: one way random effects.
Sources: See app. I.

APPENDIX I

This appendix reports the original sources for each series used in this study. Unless otherwise stated, coal = hard coal, employment = above ground + below ground, and quantity measure = metric tons.

Austria

Employment and employees killed in accidents: Wright, *Coal Mine Labor*, p. 59, adult men only, above and below ground. Coal production, p. 26, hard coal only, no lignite. *Statistisches Jahrbuch*.

Belgium

Non-salaried employees in coal mines: Wright, *Coal Mine Labor*, p. 118. 1851–87: *Statistique des accidents survenus dans les charbonnages*. 1888–99: *Statistique des mines* (*Extraits des annals des travaux publics,* vols. XLVI–LII; *Extraits des annals des mines de Belgique*, vols. I–V). 1900–2: *Annales des mines de Belgique*, vols. VI, VIII.

Belgium

Coal production: Wright, *Coal Mine Labor*, p. 113. 1851–80: *Annales des travaux publics*, vol. XL. 1881–99: *Statistique des mines* (*Extraits des annals des travaux publics*, vols. XLI–LII; *Extraits des annals des mines de Belgique*, vols. I–V). 1900–2: *Annales des mines de Belgique*, vols. VI, VIII, IX.

Belgium
Employment and employees killed in accidents: Wright, *Coal Mine Labor*, p. 141. 1851–88: *Statistique des accidents survenus dans les charbonnages* (*Extraits des annals des travaux publics*, vol. XLVII). 1889–99: *Statistique des mines, minières, carrières, etc.* (*Extraits des annals des travaux publics*, vols. XLVIII–LII; *Extraits des annals des mines de Belgique*, vols. I–V). 1900–2: *Annales des mines de Belgique*, vols. VI–VIII.

France
Coal production (bituminous, anthracite, and lignite included here): Wright, *Coal Mine Labor*, pp. 184–5. 1853–72: *Résumé des travaux statistiques*. 1873–1901: *Statistique de l'industrie minérale*. 1853–72: reported in quintals which were converted to metric tons at 10 quintals = 1 metric ton.

France
Employment of non-salaried coal plus lignite workers, and employees killed in accidents in coal and lignite mines, above and below ground: Wright, *Coal Mine Labor*, p. 213. 1853–8, 1860–72: *Résumé des travaux statistiques* (1859 employment and accident data missing and interpolated; by Conus and Conus, 'Les transformations', this was not an unusual year in fatal accident rate terms). 1873–1901: *Statistique de l'industrie minérale*.

Prussia
Coal production: Wright, *Coal Mine Labor*, p. 289. Employment (includes salaried employees): ibid., p. 308. 1852–1903, *Zeitschrift für das Berg-, Hütten- und Salinenwesen*, vols. I–LII. 1852–9: quantity in *tonnen*, converted to metric tons at 5 *tonnen* = 1 metric ton. 1860–79: quantity in *centner*, converted to metric tons at 20 *centner* = 1 metric ton.

Prussia
Employees killed in accidents: Wright, *Coal Mine Labor*, p. 326. 1852–61: *Zeitschrift für das Berg-, Hütten- und Salinenwesen, 1852–61*. 1862–1903, 1852–1903: *Zeitschrift für das Berg-, Hütten- und Salinenwesen*, vols. XI–XV, XL–LII.

UK
Coal production: Wright, *Coal Mine Labor*, p. 404. 1854–8: *Statistical Abstract of the United Kingdom*, no. 12. 1859–72: *Statistical Abstract for the United Kingdom*, no. 21. 1873–1903: *Mines and Quarries* (1901–3). Production includes coal extracted from open quarries.

UK
Employment: Wright, *Coal Mine Labor*, p. 416. *Mines and Quarries* (1900). 1883–1903: Coal Table 1903, Parliamentary Paper no. 312 of session 1903, and continuation, 1904. 1851–60: employees in coal mines only. 1861–72: employees in coal and stratified ironstone mines. 1873–82: employees in and about mines classed under the Coal Mines Regulation Act. 1883–1903: employees under the Coal Mines Regulation Act after subtracting the estimated number of persons employed in raising minerals other than coal.

UK
Deaths from accidents: Wright, *Coal Mine Labor*, p. 444. *Mines and Quarries* (1900 and 1903). 1851–60: coal mines only. 1861–72: coal and stratified ironstone mines. 1873–1903: mines classed under the Coal Mines Regulation Act.

* Author Affiliations: John E. Murray, Rhodes College; Javier Silvestre, University of Zaragoza.

[1] We received helpful suggestions from anonymous referees, Alfonso Herranz-Loncán, Alfredo Menéndez-Navarro, Eric Geerkens, and participants at the XI Labor History Conference (University of Barcelona) and the IX European Social Science History

Conference (Glasgow). The Spanish Government (projects ECO 2009-07996 and ECO 2012-33286) and the Government of Aragon (research project S27) have provided financial assistance. We are grateful to Jean-Louis Escudier for access to unpublished work and to Jörg Baten for assistance in obtaining other publications.

[2] Zola, *Germinal*, p. 224.

[3] Wright, *Coal Mine Labor*, pp. 213–14.

[4] Most, but not quite all, German coal production occurred within the boundaries of Prussia, and most of the statistics used here refer to Prussia alone. We use the terms Germany and Prussia more or less interchangeably in this essay.

[5] Bartrip and Burman, *Wounded soldiers*.

[6] Mills, *Regulating health*; MacDonagh, ‘Coal mines regulation’.

[7] Martin, ‘Allgegenwärtiger Tod’.

[8] Reid, ‘Role of mine safety’.

[9] Leboutte, ‘Mortalité’, p. 734. See also Trischler, ‘Arbeitsunfälle’.

[10] Church, *History*, pp. 320–8; Singer, Holmyard, Hall, and Williams, eds., *History of technology*, pp. 92–8. Note that the fifth volume of this great *History of technology*, which covered 1850–1900, included no reference at all to coal winning.

[11] Church, *History*.

[12] Burghardt, *Mechanisierung*.

[13] Burhop, ‘Level of labour productivity’. See also Greasley, ‘Fifty years’.

[14] Clapham, *Economic development*, pp. 232–42; Pounds and Parker, *Coal and steel*.

[15] Pounds and Parker, *Coal and steel*, p. 97.

[16] Ibid., pp. 80–3; Jevons, *British coal trade*, pp. 160–1.

[17] Pounds and Parker, *Coal and steel*, pp. 113–14; Wrigley, *Industrial growth*, pp. 12–30.

[18] Wood, ‘On safety lamps’.

[19] Dickinson, ‘Progress’.

[20] Pernolet and Aguillon, *Exploitation*.

[21] Leboutte, ‘Mortalité’, p. 727.

[22] Burat, *Les houillères*, pp. 134–70, p. 149 on cables.

[23] Abel, *Mining accidents*, pp. 5–6.

[24] Pounds and Parker, *Coal and steel*, p. 130.

[25] Lamb, ‘Coal mining’, p. 181.

[26] Burghardt, *Mechanisierung*, pp. 80–6; Lamb, ‘Coal mining’, pp. 166–7, 203; Jevons, *British coal trade*, pp. 202–5; Singer et al., eds., *History of technology*, p. 87.

[27] Tonneau, *De l’exploitation*, pp. 71–2. The French term is *gradins renversés*.

[28] Burghardt, *Mechanisierung*, pp. 81, 384. Strictly, *Firstenbau* refers to overhead stoping, but both overhead and underhand were used on diagonal veins.

[29] Marshall, *Explosives*, p. 28.

[30] Mallard and Le Chatelier, ‘Du rôle’; Neville, ‘Courrières’.

[31] Rice, *Explosibility*, pp. 19–20, 82–3.

[32] Guttmann, *Manufacture*, pp. 225–34.

[33] Hardwick and O’Shea, ‘Notes’, pp. 649–51.

[34] Leboutte, ‘Mortalité’, p. 714.

[35] Hardwick and O’Shea, ‘Notes’.

[36] Bedson and Belinfante, ‘Report’, p. 518.

[37] Anon., ‘Progress in mining’, p. 409; Nasmyth, *James Nasmyth*, pp. 426–9.

[38] A. H., ‘Nécrologie’.

[39] Anon., ‘Accidents in mines’.

[40] Church, *History*, p. 324.

[41] Arnould, *Mémoire historique*, p. 121.

[42] Burghardt, *Mechaniesierung*, p. 380; Lamb, 'Coal mining', p. 186.
[43] Lamb, 'Coal mining', p. 181.
[44] Anon., '"Capell" Patent'; discussion following Capell, 'Observations,' p. 64; Wabner, *Bewetterung*, pp. 190–2 (note the English scepticism of the Capell fan here passing directly into the German language literature); Ser, *Essai*.
[45] MacDonagh, 'Coal mines regulation', pp. 84–5.
[46] Galloway, *History*, pp. 243–6; Jevons, *British coal trade*, p. 382.
[47] On this delay, see also Mills, *Regulating health*, p. 116.
[48] Jevons, *British coal trade*, p. 382.
[49] MacDonagh, 'Coal mines regulation', p. 86.
[50] Boyer, *Unfallversicherung*, pp. 114–15.
[51] Lamb, 'Coal mining', p. 217, citing a previous edition of Burat, *Les houillères*.
[52] Abel, *Mining accidents*, pp. 9–12.
[53] Bedson and Belinfante, 'Report', p. 1131.
[54] Ibid., p. 1131.
[55] Ibid., p. 1131; Trischler, 'Arbeitsunfälle'.
[56] Abel, *Coal*, p. 16; Greasley, 'Diffusion'.
[57] Adams, 'Miner's yearly and daily output', p. 127.
[58] Walker, *Coal cutting*, p. 47.
[59] Denoël, 'Les moyens'.
[60] Burghardt, *Mechanisierung*, p. 139.
[61] Leiby, *Carroll Wright*.
[62] Wright, *Coal Mine Labor*, pp. 12, 185.
[63] Lamb, 'Coal mining', p. 186. His source was the annual *Statistique de l'industrie minérale*. We were able to add to this series data for 1896 to 1899, from the same source.
[64] Burghardt, *Mechanisierung*, p. 380. See also Verein, *Entwickelung*, Tafel IX.
[65] Compare Reid, 'Role of mine safety', p. 98, to Wright, *Coal Mine Labor*, p. 215. Further discussion of definitions in and collection of French accident statistics appears in Conus and Escudier , 'Transformations'.
[66] Wright, *Coal Mine Labor*, p. 140; Hoffman, 'Problems of labour', p. 783.
[67] Wright, *Coal Mine Labor*, pp. 27, 113, 188, 289, 407.
[68] Ibid., pp. 235, 374.
[69] Im, Pesaran, and Shin, 'Testing'.
[70] Loubère, 'Coal miners'.
[71] Banken, *Industrialisierung*, vol. I, p. 134; vol. II, pp. 123–4. For legal status of *unständige* miners in Austria, see Anon., 'Statuten'. On the share of miners who were *unständige,* see Jopp, *Insurance*, p. 103.
[72] Silvestre, 'Workplace accidents'.
[73] Boyer, *Unfallversicherung*, p. 116; Bedson and Belinfante, 'Report', p. 1131.
[74] Reid, 'Role of mine safety', pp. 111–12.
[75] The primacy of technology in the first half of the century is the conclusion reached by Hair, 'Mortality', p. 560 (on gassy mines). On the lack of effect of employers' liability regulation in Britain, see Bartrip and Burman, *Wounded soldiers*, pp. 52–3.
[76] Mills, *Regulating health*, p. 116.
[77] McIvor and Johnston, *Miners' lung*, p. 47.
[78] Treble, 'Productivity'; Kirby, 'Attendance'.
[79] The rate of change was about 0.3% annually in Belgium and 0.8% in Britain.
[80] Keller, 'Statistique des caisses'.
[81] Guinnane and Streb, 'Incentives'; Murray and Nilsson, 'Accident risk compensation'; Murray, 'Social insurance claims'.

[82] Loubère, ‘Coal miners’; Lucassen, ‘Other proletarians’.