Selecting and Evaluating Case Studies of the Economic Benefits of Research and Services at the National Institute for Occupational Safety and Health

Case Studies on Personal Dust Monitors for Coal Miners, Improved Ambulance Design, and Amputation Surveillance

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RAND SOCIAL AND ECONOMIC WELL-BEING

Prepared for the National Institute for Occupational Safety and Health

For more information on this publication, visit www.rand.org/t/RR4201

Published by the RAND Corporation, Santa Monica, Calif.

Preface

In 2017, the National Institute for Occupational Safety and Health (NIOSH) asked the RAND Corporation to develop an approach for estimating the economic benefit of its research and services and to illustrate its use through three exploratory case studies. That report, Miller et al. (2017), presented such an approach and demonstrated it using three case studies. In 2018, NIOSH asked RAND to produce this report, which builds upon prior work by developing a process for selecting case studies for evaluation, applying that selection process to a list of ten potential case studies, and providing a detailed analysis of the benefits associated with three selected case studies. Together, these reports help build a foundation for evaluating the broader societal benefits provided by NIOSH, both by providing estimates of the benefits associated with specific NIOSH activities and by providing NIOSH with methods and examples for consistently evaluating the societal impact of its own work.

This research was sponsored by the U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, NIOSH, under contract 75D30118F01560 with NIOSH.

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Summary

In 2017, the National Institute for Occupational Safety and Health (NIOSH) asked the RAND Corporation to develop an approach for estimating the economic benefit of its research and service activities and to illustrate its use through three exploratory case studies. Miller et al. (2017) provided such approach and illustrated its use through three exploratory case studies. This report builds upon that work by developing a process for selecting case studies for evaluation, applying that selection process to a list of ten potential case studies, and selecting three case studies from this list for detailed analysis.

NIOSH identified ten potential case studies, and RAND traced the elements of these case studies from the input hazard to the potential changes in health outcomes for workers and other affected individuals. In parallel, RAND identified attributes of cases studies that NIOSH might use to identify which cases to evaluate in further detail:

- **Feasibility.** There must be enough information available to anticipate the ability to establish and quantify the link between NIOSH activities and worker outcomes without extensive new data collection.
- **Impact.** This is defined in terms of (a) the number of potentially affected workers, (b) the extent to which there is evidence that control measures resulting from on NIOSH's work are actually implemented, and (c) the actual or anticipated reduction of risk resulting from the implementation of these control measures.
- **Attribution.** There must be clear evidence that changes in worker safety and health occurred in response to NIOSH efforts.
- **Balance.** When taken together, the cases must represent a diversity of program areas.
- **Institutional priorities.** The cases must represent current areas of particular interest to NIOSH.

Based on these attributes, we selected three case studies: Personal Dust Monitors for Coal Miners, Improved Ambulance Design, and Improved Amputation Surveillance.

In the Personal Dust Monitors for Coal Miners case, we found NIOSH's activities, which included awarding research grants, collaborating with industry and labor in testing and developing prototypes, disseminating research findings, and conducting outreach to miners, played a major role in the development and adoption of continuous personal dust monitors (CPDMs) for coal miners. Without NIOSH's contribution, the achieved reductions in exposure to respirable coal mine dust may not have been as successful, and improvements in workplace practices based on corrective actions linked to CPDMs would have been less likely to occur.

- We estimate the avoided medical costs and productivity losses for cases of fatal and nonfatal respiratory disease due to the reduction in exposures to respirable coal mine dust after the adoption of CPDMs ranged from $3.6 million to $8.0 million on an annualized basis over 65 years, depending on the attribution of fatal cases avoided by age 73 or 85 and whether a 3-percent or 7-percent discount rate is used.
- We estimate the economic benefits based on willingness-to-pay estimates associated with risk reductions in fatal and nonfatal respiratory disease ranged from $10.4 million to $25.3 million per year, depending on the attribution of fatal cases avoided by age 73 or 85 and whether a 3-percent or 7-percent discount rate is used.

In the Improved Ambulance Design case, NIOSH's impact on ambulance design has been the result of a steady stream of partnerships with stakeholders. NIOSH has focused on improving the design of the patient compartment and its contents, both by working directly with manufacturers and by collaboration with standard-setting organizations. NIOSH continues to play a pivotal role in these partnerships, and many of the design changes may not have happened without NIOSH's involvement. We estimate the benefits associated with three different sets of assumptions about the effectiveness of the ambulance redesign in preventing injuries or reducing injury severity: the patient compartment becoming as safe as the back seat of a standard four-door passenger vehicle, the patient compartment becoming as safe as ambulance driver position, and improvements in patient compartment safety being consistent with literature on seat belt effectiveness in similar vehicles.

- If the ambulance redesign causes the patient compartment of ambulances to become as safe as any of the sets of assumptions we modeled, this could result in an annualized benefit that ranges from $2.5 million to $8.0 million from 2017 to 2050, depending on the modeling assumptions and whether a 3-percent or 7-percent discount rate is used. Benefits per year increase over time.
- If the ambulance redesign causes the patient compartment of ambulances to become as safe as any of the sets of assumptions we modeled, this could result in $24 million to $74 million in avoided "value of a statistical life" losses from 2017 to 2050, depending on the modeling assumptions and whether a 3-percent or 7-percent discount rate is used. Benefits per year increase over time.
- There are many uncertainties associated with these estimates, and the ultimate impact could vary significantly. Due to data limitations, these estimates examine only injuries associated with collisions, and do not include injuries associated with noncollision events.

In the Improved Amputation Surveillance case, we found that a Michigan amputation surveillance program funded by NIOSH led to referrals that found more violations and assessed higher monetary penalties than typical inspections in the state between 2003 and 2018. While our estimates are not causal, it is likely that the surveillance program helped the Michigan Occupational Safety and Health Administration better target inspections, leading to a more efficient allocation of scarce resources such as inspection personnel. Inspections from the surveillance program found 2.60 times as many violations as other inspections and assessed approximately 2.45 times the amount of a typical inspection in monetary penalties. The Michigan program substantially influenced other state programs such as the one in Massachusetts. The program also provided better information on the extent of amputations in Michigan and in which industries and firms amputations had occurred that were not reported in other sources.

- While our estimates are not causal, if we assume that inspections that occurred due to the Michigan amputation surveillance program would not have occurred but for the program and that resources utilized for these inspections would have been used to conduct inspections similar to the average inspection measured in our data had the program not existed, then we can provide some rough numbers of the effects of the program on these proximate outcomes. Under these assumptions the program increased the number of violations discovered by about 96 violations per year and increased total initial penalties by approximately $47,300 per year.
- The available data do not enable us to quantify the benefit of the program on worker safety and reduction in amputations or measure the spillover effects of the program. While more data are necessary to fully quantify the benefits of surveillance programs and to establish a causal link between surveillance, inspections, and worker safety, our preliminary analysis suggests that NIOSH-supported surveillance programs likely have positive benefits to society.

Acknowledgments

This report exists only because staff at the National Institute for Occupational Safety and Health (NIOSH), as well as other stakeholders, generously shared their time and expertise. In particular, we thank Tim Bushnell, Rene Pana-Cryan, Brian Quay, and Tapas Ray of NIOSH, who ensured we had access to all relevant information and stakeholders, and who were patient and thoughtful partners throughout. We also extend our appreciation to a large number of NIOSH staff that shared their time and subject matter expertise, including Jay Colinet, Emily Haas, Steve Michler, W. Randy Reed, Randall Smith, LaTasha Swanson, Donald Tuchman, Jim Green, Audrey Reichard, Bill Lindsley, Steve Martin, and Rosa Rodriguez-Acosta. We also thank the many individuals outside of NIOSH who spoke with us. In particular, we are grateful to Ken Rosenman for sharing both data and expertise. We are particularly grateful to our RAND colleague Chris Nelson for his assistance with the case study selection process and for his guidance throughout this effort. We also thank our colleague Eric Landree for sharing his insights on the elements of a case study. Finally, we thank Phil Armour and John Mendeloff for providing thoughtful reviews that helped improve the quality of this final report.

Abbreviations

BLS	Bureau of Labor Statistics
CASS GVS	Commission on Accreditation of Ambulance Services' Ground Vehicle Standard for Ambulances
CDC	Centers for Disease Control and Prevention
CMDPSU	coal mine dust personal sampler unit
COPD	chronic obstructive pulmonary disease
CPDM	continuous personal dust monitor
CWHSP	Coal Workers' Health Surveillance Program
CWP	coal worker's pneumoconiosis, a.k.a. "black lung"
DOT	Department of Transport
ECWHSP	Enhanced Coal Workers' Health Surveillance Program
EMS	emergency medical services
EPA	Environmental Protection Agency
FARS	Fatality Analysis Reporting System
FEV1	forced expiratory volume
FTA	failure to abate
FY	fiscal year
GAO	Government Accountability Office
GSA	General Services Administration
IIF	Injuries, Illnesses, and Fatalities
MDHHS	Michigan Department of Health and Human Services
MIOSHA	Michigan Occupational Safety and Health Administration
MMCRDM	machine mountable continuous respirable dust monitor
MSA	Metropolitan Statistical Areas
MSHA	Mine Safety and Health Administration
MSU	Michigan State University
NAICS	North American Industry Classification System

NASEMSO	National Association of State EMS Officials
NASS-GES	National Automotive Sampling System–General Estimates Data System
NEISS-Work	National Electronic Injury Surveillance System
NFPA 1917	National Fire Protection Association Standard for Automotive Ambulances
NHAMCS	National Hospital Ambulatory Medical Care Survey
NHTSA	National Highway Traffic Safety Administration
NIOSH	National Institute for Occupational Safety and Health
NMRD	nonmalignant respiratory disease
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PMF	progressive massive fibrosis
R&P	Rupprecht and Patashnick Co., Inc.
REL	recommended exposure limit
SAE	Society of Automotive Engineers
SCBA	self-contained breathing apparatus
SOII	Survey of Occupational Injuries and Illnesses
VSL	value of a statistical life
WL	work location
WTP	willingness to pay
YPLL	years of potential life lost

1. The Case Study Selection Process

Introduction

The National Institute for Occupational Safety and Health (NIOSH), which is housed within the Centers for Disease Control and Prevention (CDC), was established to help ensure U.S. workers operate in safe and healthful working conditions. NIOSH supports this goal by funding related efforts by external researchers; developing and testing engineering controls, personal protective equipment, and other technologies; providing educational information, guidance, and training; as well as other services (NIOSH, 2018b).[1]

NIOSH must prioritize its investments in workplace safety and health research and services to make the best use of available funding, and must demonstrate the value of that funding. Research priorities are based on the number of workers at risk for a particular injury or illness, the seriousness of a hazard or problem, and the likelihood that new data or approaches can make a difference (NIOSH, 2012b). However, there are a number of challenges in understanding the benefits associated with this or any agency's research activities. First, as seen in the case studies presented in this report, it can be difficult to accurately quantify the impact of activities on the underlying risk or associated outcomes. Second, benefits may not accrue until many years in the future. Third, much of NIOSH's work is done in collaboration with many government, academic, and private industry partners, making it difficult to isolate or conceptually define any individual organization's contribution. Fourth, because NIOSH is a public agency working for the common good, there is often no market price mechanism to allow for the easy assessment of the economic benefit of NIOSH's work to society.

In 2017, NIOSH asked the RAND Corporation to develop an approach for estimating the economic benefit of its research activities and illustrate its use through three exploratory case studies. That report, Miller et al. (2017), developed such an approach and demonstrated it using three case studies. Because that report was conducted on a short timeline, the three selected case studies were selected quickly based on cases "that had clear and documented connections between the NIOSH activities and any intermediate or end outcomes (i.e., reduction in workplace injuries, illnesses, or fatalities) and as mentioned above, focused on cases with readily accessible data" (Miller et al., 2017). In 2018, NIOSH asked RAND to build upon that work by developing

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[1] The main legislative underpinnings of NIOSH are the Federal Coal Mine Health and Safety Act of 1969 (Pub. L. No. 91-173, amended by Pub. L. No. 95-164 in 1977 or MSH Act; also known as the Coal Act) and the Occupational Safety and Health Act of 1970 (Pub. L. 91-596; also known as the OSH Act). The Occupational Safety and Health Administration (OSHA), which was also established as part of the OSH Act, is a separate organization in the Department of Labor that is responsible for developing and enforcing workplace safety and health regulations.

a process for selecting case studies for evaluation, applying that selection process to a list of ten potential case studies, and selecting three case studies from this list for detailed analysis. The goal is that this process will not only provide ex-post guidance on which projects might be evaluated, but will also provide NIOSH guidance on what makes it easier or harder to evaluate its work. Both reports are also intended to help NIOSH communicate its impact to the public, stakeholders, and policymakers. In doing so, these reports may influence the adoption of the evaluated risk mitigation measures. Together, these reports help NIOSH build a foundation for consistently evaluating the societal impact of its own work.

Role of NIOSH in This Report

In keeping with the precedent set by Miller et al. (2017) and in the interest of transparency, we note NIOSH's important role in this report. NIOSH identified and provided the ten potential case studies, and RAND developed the framework for choosing between them. RAND decided which case studies to pursue, although as the methodology clearly notes, NIOSH's institutional priorities were one of several important factors in determining which cases to evaluate in detail. Given the need for detailed information about NIOSH's activities, we relied considerably on input from NIOSH researchers, as well as from other stakeholders outside of NIOSH. Throughout, we considered suggestions made by NIOSH and incorporated these into the analysis and report, where deemed appropriate. RAND alone developed the methodology and conducted the analysis, and the terms of contract for this project gave RAND full editorial authority over the content of the report.

Organization of This Report

This first chapter articulates a process for selecting case studies, discusses how cases are defined, and presents ten examples of potential case studies. It then describes the attributes that determine one's ability to draw useful conclusions from a case study, and walks through the process of using these attributes to select three of these potential case studies for further analysis.

Chapters 2, 3, and 4 provide detailed evaluations of the three selected case studies: Personal Dust Monitors for Coal Miners, Improved Ambulance Design, and Improved Amputation Surveillance. Each of these chapters describes the context of the case study and the activities NIOSH conducted. Each chapter attempts to estimate the societal benefits provided by NIOSH's work based on the value of a statistical life (VSL) and on medical costs and lost productivity. Each chapter also discusses the limitations and assumptions associated with each case. Chapter 5 summarizes and synthesizes the findings from these case studies and Miller et al. (2017).

Elements of a Case Study

The purpose of this report is to estimate the societal benefits provided by NIOSH activities through three case studies. Because NIOSH activities focus on improving worker safety and health, each case study will assess the impact of NIOSH research and services on the safety and health outcomes of a targeted population that is exposed to one or more health hazards. Each case study is intended to serve as a clear, data-based story that identifies and describes the manner and extent to which NIOSH activities caused and/or contributed to measurable improvements in health, safety, and any other relevant outcomes.

Although each case study tells a unique story, there are common elements to all case studies. Each case study begins by identifying the population of workers exposed to a specific health or safety **hazard**. Examples typically involve dangerous work environments that increase workers' risk of certain diseases or injuries. NIOSH may discover the hazard itself through surveillance activities or may be alerted to it by external parties.

In response to this hazard, NIOSH engages in a variety of **activities** aimed at producing **outputs** that will help mitigate the hazard. Examples of NIOSH activities include research, surveillance, and training. These activities lead to outputs such as new information about the causes of a hazard, the identification of new hazards, or assessments of the effectiveness of existing hazard mitigation efforts. Outputs of these activities could also include new ideas for potential solutions to the hazard. These may include engineering solutions such as new safety equipment or design changes to existing equipment, or administrative and policy changes that alter the work environment or how workers interact with their environment. Examples include the development of new or improved personal protective equipment, or suggesting changes in production processes.

In order for these research outputs to improve workers' safety and health, they need to be **transferred** to the **stakeholders** who will use the research results in practical settings. The transfer of NIOSH research outputs involves disseminating information through the publication of reports, new releases, databases, presentations, or training programs. These efforts to transfer knowledge are targeted at particular groups called stakeholders. The **end stakeholder** is usually the worker who is facing the health hazard. However, reaching workers often requires first transferring information to **intermediate stakeholders**, such as companies in the affected industry, state or federal regulatory agencies, standards organizations, or other entities. These intermediate stakeholders in turn adopt new preventative measures such as new laws, regulations, or changes in practice, based on the outputs provided to them by NIOSH. These preventative measures serve as **intermediate outcomes**. Transferring research outputs to multiple intermediate stakeholders, who in turn transfer intermediate outputs to multiple end stakeholders, can quickly scale up the impact of NIOSH's activities.

The impact of the research on worker safety and health is assessed through changes in those **end outcomes**. For example, a case study might assess how NIOSH research led to a reduction in a particular type of workplace injury or illness. In general, the impact of NIOSH research should be thought of as the difference between observed outcomes or predicted future outcomes versus the outcomes that might have been observed without NIOSH involvement.

One challenge in defining a case study is that there are often multiple interwoven hazards, activities, outputs, stakeholders, and outcomes. These components need to be aggregated or disaggregated to define the scope of the case study. There are multiple ways to define the scope of a case study, and the appropriate definition may depend on the objectives for which the case study is being evaluated. A case can be defined by the type of hazard to which a group of workers is exposed, such as a case study that evaluates the impact of several activities aimed at reducing a certain type of injury for a certain type of worker. Alternatively, a case might group several related hazards, such as a case study that evaluates the overall impact of multiple changes to a work environment where workers were exposed to these hazards.

The goal of this effort is to evaluate the impact of specific NIOSH activities, so the appropriate method for defining case studies is to look at a specific activity or cluster of coordinated activities. Because NIOSH research and services activities are typically grouped around mitigating a particular hazard for a particular type of worker, the case studies we consider are usually defined by a particular hazard or group of related hazards to which a particular group of workers is exposed.

Identification of Potential Case Studies

Based on the above framework and institutional knowledge, NIOSH identified a list of ten potential case studies and provided RAND with documentation from public sources and associated NIOSH experts. Starting with these potential case studies as examples, RAND and NIOSH worked together to develop a process for determining whether potential cases could currently be successfully evaluated, and for selecting three specific cases to evaluate in further detail. In some cases, additional public documentation was found during the course of review. This process was indirectly informed by similar prior evaluations, documented in Miller et al. (2017). This chapter documents this process in detail because the identification and selection process itself provides value in highlighting what is required to successfully evaluate the impact of NIOSH research and service activities. This process can provide NIOSH researchers with a method for thinking about which research opportunities to pursue. In this spirit, RAND assisted NIOSH with internal training exercises aimed at helping NIOSH researchers understand how to evaluate the potential societal impact of their own research.

Table 1.1 lists the identified potential case studies. It also provides a brief description of the affected population, the hazard to which that population was exposed, and the NIOSH research activities and outputs. This summary is based on information collected from published reports and other sources that RAND reviewed to describe each element of the case study and document the availability of supporting data. The collected information helped inform the subsequent case study selection process.

Table 1.1. Potential Case Studies

	Case Study	Description of Population and Health Hazard	Brief Description of NIOSH Activities and Outputs
1	Personal Dust Monitors for Coal Miners	NIOSH and the U.S. Mine Safety and Health Administration (MSHA) observed an increase in prevalence of coal workers' pneumoconiosis (CWP, or "black lung") in 2005, 2006, and 2007 (and more cases in younger miners).	Since 1970, NIOSH has administered the Coal Workers' Health Surveillance Program (CWHSP), and NIOSH later launched the Enhanced Coal Workers' Health Surveillance Program (ECWHSP). NIOSH published a variety of reports and studies on the hazard, created criteria for recommended standards, and partnered with Thermo Fisher Scientific to design and test a continuous personal dust monitor (CPDM), as well as other related activities.
2	Oil and Gas Thief Hatches	Oil and gas workers can be exposed to hydrocarbon gases and vapors (HGV) and oxygen (O_2)-deficient atmospheres when opening the "thief hatch" of hydrocarbon storage tanks to check tank contents. Exposure to high levels of HGV can cause lethal cardiac arrhythmia; severe exposure to low levels of O_2 can result in rapid loss of consciousness and/or death.	In 2013, NIOSH and the National Occupational Research Agenda Oil and Gas Extraction Sector Council developed the Fatalities in the Oil and Gas Industry database. After identifying the risk, NIOSH published information in blogs, reports, alerts, and presentations to stakeholders, including recommendations to regulators.
3	Taxicab Cameras	The taxi and limousine industry is a disproportionately dangerous working environment for drivers who can be assaulted or murdered.	NIOSH supported two studies (published in 2013 and 2014) on safety measures (cameras and partitions) to reduce homicides of taxi cab drivers. At least two U.S. cities (Philadelphia and New Orleans) based ordinances mandating security cameras in taxis on this research.
4	Musculoskeletal Diseases in Poultry Processing Plants	Workers employed in the poultry processing industry are at high risk for carpal tunnel syndrome from a combination of forceful exertions and high repetition.	NIOSH investigations of two poultry plants in 2014–2015 identified the risk. This work was a continuation of prior NIOSH research, starting from the late 1990s, that was intended to help reduce the incidence and severity of musculoskeletal disorders. NIOSH published articles based on the investigations, and disseminated information to industry and federal agencies.
5	Preventing SCBA Failure	Firefighter fatalities were occurring due to the failure of self-contained breathing apparatus (SCBA) facepiece lenses due to thermal degradation.	NIOSH provided fatality investigations to the National Fire Protection Association, which in turn issued alerts and revised standards.

	Case Study	Description of Population and Health Hazard	Brief Description of NIOSH Activities and Outputs
6	Reduction in Exposure to Hazardous Drugs in Health Care	Health care workers are at risk of a variety of adverse health outcomes caused by exposure to hazardous medicinal drugs.	NIOSH, the Food and Drug Administration, and OSHA have jointly conducted a biennial review to classify old and new drugs, compiling a list of hazardous drugs in health care settings. NIOSH research has focused on exposure risks and prevention measures, such as a closed-system drug transfer device. NIOSH has issued alerts, published reports, and provided grants to investigate ways to reduce exposure.
7	Mining Hearing Loss	Noise-induced hearing loss is the most common occupational disease among workers in the mining industry. Hazardous noise exposures are more prevalent in this sector than in any other major U.S. industrial sector. NIOSH studies have shown that ca. 90% of coal miners and 49% of metal/nonmetal miners have a hearing impairment by age 50.	NIOSH has (1) worked with manufacturers to develop and commercialize noise control technologies for the mining industry; (2) developed and published research on technologies to motivate miners to implement noise controls, participate in administrative exposure management, and use hearing protection effectively; and (3) published research on noise-induced hearing loss, including evaluations of the effectiveness of the different noise controls.
8	Improved Ambulance Design	Injuries and fatalities among emergency medical services (EMS) workers and patients can occur when ambulances are involved in a crash. Factors contributing to EMS worker injuries that occur in the patient compartment include loose or unrestrained equipment, patient compartment layout, and lack of seat belt use.	NIOSH engaged in surveillance efforts, collecting data for the National Electronic Injury Surveillance System (NEISS-Work). Based on this work, the National Highway Traffic Safety Administration (NHTSA) funded a larger study and data collection effort. NIOSH produced a new database, a publication, test methods, an informational video series, and engaged in various outreach efforts.
9	Improved Amputation Surveillance	Unsafe worksite conditions can create undue risk of injuries that result in amputations. OSHA inspects worksites in the United States to monitor compliance with laws and regulations and to make sure working conditions are safe for workers. However, there is only about one OSHA compliance officer for every 59,000 workers in the United States.	NIOSH funding was used to develop a multisource surveillance system to better target worksite inspections and to evaluate this system. The system is based on workers' compensation claims and medical records of patients treated for work-related amputations. NIOSH has also funded other work related to surveillance in other states and for other injury types (e.g., burns).
10	Alaska Commercial Fishing Training	Workers who are immersed in water due to falling overboard or being on a sinking or capsizing vessel are at high risk of death due to drowning or hypothermia, particularly in cold water.	In 1985, the National Oceanic and Atmospheric Administration (health care) and others provided funds to start regional safety training programs for commercial fishermen, although NOAA funding ended many years ago. Today, most funding comes from the Coast Guard, NIOSH, course fees, and locally raised funds.

Method for Selecting Cases for Evaluation

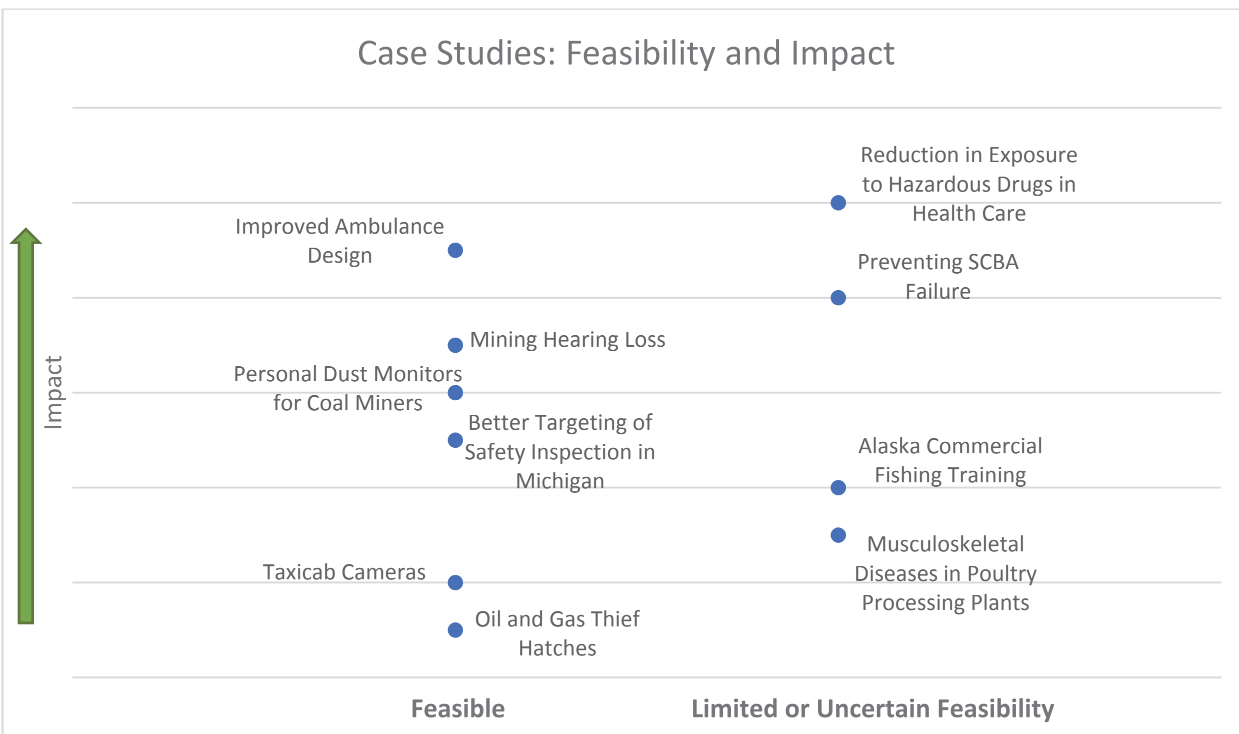
To select three case studies for in-depth analysis, we sequentially considered a variety of attributes that affect our ability to draw useful conclusions from the case study. We assessed the elements of each case study, as well as each of the below attributes, based on the public source data and other documentation provided by NIOSH as part of a quick-turn review that documented the elements of each case study, as described in Table 1.1.

1. **Feasibility.** The first and most important of these attributes is feasibility, which means that there must be enough information available to anticipate the ability to establish and quantify the link between NIOSH activities and worker outcomes without extensive new data collection. In the absence of clear documentation of NIOSH's activities, the observed or forecasted change in workers' safety and health, and the events through which these elements are connected, a case was deemed infeasible. Cases deemed infeasible were not selected for evaluation. This does not imply that NIOSH had no impact in these cases, but only that NIOSH's impact would be difficult to measure with reasonable accuracy. A case that is currently infeasible might become feasible at a later point as more information becomes available. RAND documented specific information gaps for all cases to help identify what information would make a case feasible.
2. **Impact and attribution.** Cases that passed the feasibility screen were assessed in terms of the magnitude of likely impact, and the ability to attribute that impact to NIOSH. We defined impact in terms of (a) the number of potentially affected workers, (b) the extent to which there is evidence that control measures resulting from NIOSH's work are actually implemented, and (c) the actual or anticipated reduction of risk resulting from the implementation of these control measures.
3. **Attribution.** For attribution, we considered whether there is clear evidence that changes in worker safety and health occurred in response to NIOSH efforts. Attribution can be particularly challenging in environments where multiple organizations are involved in protecting workers from the relevant hazard(s). Other things being equal, cases with larger impact tend to be of interest to a broader audience, and cases with clearer attribution tend to be offer a more compelling assessment of NIOSH's impact.
4. **Balance.** All else equally, we gave greater weight to cases that, when taken together, represent a diversity of program areas.
5. **Institutional priorities.** Finally, after evaluating cases on the criteria described above we gave greater weight to current areas of particular interest to NIOSH. Another institutional factor might be the consideration of which case studies NIOSH can complete in-house versus which case studies are best suited for evaluation by an external independent research organization.

The criteria described here reflect the purpose of this report, which is to help NIOSH communicate its impact to the public, stakeholders, and policymakers. To successfully meet this goal it is important and appropriate to focus on evaluations that address topics where evaluation is demanded. The criteria are not designed, for instance, to ensure the case studies provide a representative sample of all NIOSH activities or to determine the average, maximum, or minimum impact of NIOSH research and services. RAND is devoted to the analyses of each selected case being uncompromisingly unbiased, objective, and transparent.

Because more than three cases were deemed feasible, an additional attribute had to be considered to select which three cases to examine in further detail. The additional attribute selected was the anticipated magnitude of the outcome or impact. We focused on the ordinality of anticipated magnitude rather than attempting to calculate cardinality, because precise quantification of magnitude involves conducting a complete evaluation and the purpose of this exercise is to determine where to focus limited evaluation resources. For this reason, the *y*-axis in Figure 1.1 has no values—it only reflects an anticipated ranking. Further, because anticipated magnitude is determined on a case-by-case basis, the precise determination of which of two similar cases has a larger anticipated magnitude can be subjective or unclear. This effort is not designed to precisely differentiate between two cases of similar magnitude, so little stock should be placed on the difference in magnitude between cases that are at similar locations on the *y*-axis. This metric is designed to help guide the case study selection process by providing a structure that identifies and records large differences in anticipated magnitude.

Figure 1.1. Feasibility and Impact of Case Studies



For examples of how anticipated magnitude was evaluated, compare the two cases we ranked as having the lowest and highest impact among feasible cases: the Oil and Gas Thief Hatches case and the Improved Ambulance Design case. In this Oil and Gas Thief Hatches case, exposure to hydrocarbon gases and vapors caused a total of nine recorded fatalities (and an unrecorded number of injuries) between January of 2010 and March of 2015. New industry standards and proposed changes to federal regulations could promote safer methods for crude oil measurement, but even the largest possible impact of eliminating all fatalities would be preventing approximately two fatalities per year at most. In comparison, approximately 4,000 EMS workers ended up in hospital emergency departments in 2017 due vehicle-related injuries (NIOSH, 2019c). NIOSH efforts to redesign in-patient compartments to reduce the amount of loose or unrestrained equipment, and to enable EMS workers to more easily use seat belts while working, could save a significantly larger number of lives and potentially prevent thousands of injuries each year. Both research efforts are important and meaningful, but focusing on cases that have larger anticipated impacts would prioritize the ambulance design case over the thief hatches case.

As noted above, we also considered NIOSH's institutional needs and the pursuit of diverse case studies to finalize the three cases selected for detailed analysis. For example, determining how to quantitatively evaluate the impact of NIOSH training programs could greatly expand NIOSH's capability to assess its research and services. Although we did not select a training program for detailed evaluation, we did ensure that at least one potential case study, Alaska Commercial Fishing Training, was a NIOSH training program to consider how such programs might be successfully evaluated.

Finally, examining case studies that focus on different populations can help convey the benefits of NIOSH's research to a larger and more diverse audience. For this reason, we avoided examining both of the cases involving miners in order to include a case study that affects workers in other industries.

Cases Selected for Detailed Evaluation

Why Cases Were Deemed Infeasible

Figure 1.1 visualizes how we evaluated the set of potential case studies listed in Table 1.1. As defined above, feasibility refers to whether there is enough information available to establish and quantify the link between NIOSH activities and worker outcomes without extensive new data collection. A common challenge is that NIOSH's impacts frequently include improvements in the monitoring of the risk exposure itself, meaning it is sometimes difficult to objectively measure worker outcomes prior to NIOSH's involvement. The *x*-axis of the graph in Figure 1.1 shows feasibility, with cases that were judged to be feasible on the left and cases that were judged to have limited or uncertain feasibility on the right. Feasible cases included Personal Dust Monitors for Coal Miners, Oil and Gas Thief Hatches, Taxicab Cameras, Mining Hearing Loss, Improved Ambulance Design, and Improved Amputation Surveillance. Four cases—Preventing SCBA Failure, Musculoskeletal Diseases in Poultry Processing Plants, Reduction in Exposure to Hazardous Drugs in Health Care, and Alaska Commercial Fishing Training—were deemed likely to face significant feasibility challenges, and thus appear on the right-hand side of the graph.

Determining feasibility involves a degree of subjective judgment. In the case of Preventing SCBA Failure, there was no quantitative data available on the adoption of prevention measures, either in the form of new technology or changes in frontline practice. However, the case might be deemed feasible if we were willing to rely on expert judgment for such information. In the case of Musculoskeletal Diseases in Poultry Processing Plants, after the release of NIOSH's findings and recommendations, the U.S. Department of Agriculture's Food Safety and Inspection Service decided to change the New Poultry Inspection System to cap the maximum evisceration line speed for plants at 140 birds per minute (bpm), instead of the proposed 175 bpm. However, there were no data available on the number of poultry processing workers who were subject to higher line speeds before the cap. Again, it is possible that industry experts might be able to provide such information. However, this case would still face additional challenges, because it would be difficult to separate the impact of reduced line speed from the impact of other changes NIOSH recommended. Reduction in Exposure to Hazardous Drugs in Health Care was deemed infeasible without significant restriction in scope; more specific cases on pharmaceutical compounding or handling of chemotherapy drugs each may or may not be feasible. Finally, the Alaska Commercial Fishing Training case was deemed infeasible without a better understanding of the selection process by which individuals enter training, creating concern that it might be difficult to separate between the benefits of training and the benefits of access to life-saving equipment. There was some variation in the availability and enforcement of training regulations, but it was unclear whether this variation was related to the local risks.

Which Three Cases Were Selected and Why

We began by restricting consideration to the six cases studies we believed were potentially feasible. As shown by the challenges faced by the selected case studies, this remains an imperfect process because some technical challenges may not be realized without more detailed assessment. Figure 1.1 ranks the cases that were anticipated to be feasible based on anticipated impact. Based on our initial assessment, we were concerned that, while impact estimation was feasible, the Taxicab Cameras and Oil and Gas Thief Hatches cases were not associated with a large enough number of injuries or fatalities to pursue a complex, in-depth analysis of the benefits by RAND. For the remaining four cases, it was determined that the three cases studies that would be selected should each evaluate different groups of workers to meet priorities over balance; hence we would need to choose between the two cases related to mining. We selected Personal Dust Monitors for Coal Miners over Mining Hearing Loss in consideration of NIOSH's institutional priorities. Unrelated to this project, NIOSH was in the process of planning to present a panel of scientists with documentation on the impacts associated with various NIOSH research projects, including Personal Dust Monitors for Coal Miners. It was determined that an independent case study from RAND overlapping with a topic being considered by the panel might provide valuable synergies, although the timing of the studies ultimately did not align.

For these reasons—the desire to focus analytic time and resources on cases with larger impacts, the desire to evaluate case studies representing diverse workforces, and the desire to be supportive of NIOSH's institutional priorities—we selected three case studies: Personal Dust Monitor for Coal Miners, Improved Ambulance Design, and Improved Amputation Surveillance.

2. Personal Dust Monitors for Coal Miners

This case study estimates the impact of NIOSH's efforts in developing, testing, and advancing the adoption of CPDMs to reduce the incidence of respiratory disease among coal miners. Inhalation of excessively high levels of respirable coal mine dust can lead to the development of respiratory diseases, including CWP or "black lung," progressive massive fibrosis (PMF), and chronic obstructive pulmonary disease (COPD), which includes severe emphysema (Colinet et al., 2010). Coal miners with these progressive diseases are also at increased risk of death due to nonmalignant respiratory disease (NMRD). CWP has been the underlying or contributing cause of death for more than 78,000 coal miners since 1968 in the United States (NIOSH, 2017b). NIOSH surveillance data indicate that the prevalence of CWP, which declined substantially between 1970 and the late 1990s, increased for several years in the early 2000s, and that more cases of the disease were appearing in younger miners (NIOSH, 2008). According to a recent NIOSH study, after reaching a low point in the 1990s, now more than 10 percent of miners examined in the CWHSP with 25 or more years of tenure have been diagnosed with CWP (Blackley, Halldin, and Laney, 2018). In central Appalachia, which includes Kentucky, Virginia, and West Virginia, more than 20 percent of long-tenured miners examined in the CWHSP were found to have CWP.

Based on recommendations from the U.S. Department of Labor in the 1990s, NIOSH issued a request for proposal to develop a wearable personal coal dust monitor capable of providing real-time continuous and end-of-shift measurement of respirable coal mine dust. The technology, developed through a research contract with Rupprecht and Patashnick Co., Inc. (R&P), allows miners to take corrective actions based on these measurements to reduce occupational exposure to respirable coal mine dust. NIOSH, through an informal partnership with industry, labor, and MSHA, collaborated in product development as well as laboratory and field testing of the prototype CPDM. NIOSH published reports finding the prototypes provided accurate readings of a miner's dust exposure and were wearable and durable during mine testing. In 2009, NIOSH and MSHA certified the first commercial CPDM for use in coal mines in the United States. In 2010, MSHA proposed a rule to reduce miners' exposure to respirable coal mine dust, which mandated the use of CPDMs for sampling certain high-risk occupations (MSHA, 2010). MSHA promulgated the final coal mine dust rule in 2014, which led to widespread adoption of the CPDM when the new rule required mine operators to use the CPDM for compliance sampling beginning on February 1, 2016 (MSHA, 2014b).

The benefits of the CPDM include (1) real-time measurement, which allows workers to immediately adjust their position (e.g., moving upwind or further away from a dust source) or adjust control technologies to reduce exposure to excessively high dust concentrations; (2) a time-correlated dust data card and data file that can be reviewed by mine operators and workers to identify activities contributing to higher dust concentrations and help change future work practices (e.g., adjusting the ventilation or altering mining practices to avoid releasing excessive dust); and (3) a more tamper-resistant unit that improves the reliability of operator samples and incentivizes mine operators to take precautions to avoid excessive concentration measurements—compliance sampling violations could require a mine to shut down a mechanized mining unit (MMU) until a new ventilation plan is approved by MSHA and implemented in that MMU. Based on visits to several mines during 2016 and 2017, NIOSH researchers found that, in response to reviewing the information provided by CPDMs, miners identified higher dust concentrations at various times and attributed increases in exposure to specific activities—something they were not previously able to do using gravimetric samplers (Haas and Colinet, 2018). Having a time record allowed miners to take corrective actions to further reduce exposures.

In this chapter, we examine NIOSH's role in the development and adoption of the CPDM and assess the overall economic impact. The chapter begins by providing a narrative description of the economic impact of black lung, federal government actions related to the regulation of respirable coal mine dust exposure, and surveillance of coal workers' health. Next, we discuss NIOSH's activities relating to the CPDM, adoption of the new technology, and the effectiveness of the dust monitors in reducing workers' exposure to respirable coal mine dust. Finally, we provide estimates of the economic benefits of the illnesses and fatalities likely to be averted due to the adoption of CPDMs and consider NIOSH's role in contributing to these benefits.

The Cost of Black Lung

The costs to workers impacted by black lung and their families are severe. The Department of Labor estimates that the average annual cost for medical treatment in fiscal year (FY) 2017 was approximately $6,980 per miner (Government Accountability Office [GAO], 2018). Miners with CWP are also at higher risk of impaired lung function, disability, and premature death. Since 1970, the U.S. government has paid nearly $47 billion in benefits to miners disabled due to respiratory diseases, including CWP, or to their survivors through the Black Lung Benefits Program (Department of Labor, undated). As of 2019, the monthly benefit ranged from about $660 for miners with no dependents to about $1,320 for miners with multiple dependents (Szymendera and Sherlock, 2019). The Black Lung Disability Trust Fund ("Trust Fund") is primarily funded through an excise tax on coal produced and sold domestically,[2] but also borrows from the Department of the Treasury's general fund if benefit payments exceed excise tax revenues. Because expenditures have consistently exceeded revenues, the Trust Fund has borrowed from the Treasury almost every year since 1979 (GAO, 2018). The Trust Fund paid

[2] The excise tax on coal excludes lignite coal and exported coal.

about $184 million in benefits to more than 25,000 coal miners and their dependents in FY 2017 with revenues of about $450 million, but it also borrowed about $1.3 billion to cover debt repayments. Further challenging the solvency of the Trust Fund, on January 1, 2019, the excise tax reverted from $1.10 to $0.50 per ton for coal from underground mines and from $0.55 to $0.25 per ton for coal from surface mines (to the levels set when the fund was established in 1978) as Congress declined to extend the tax on coal production that had been in place since 1986.

Overview of NIOSH's Activities Related to Coal Mine Dust Exposure

This case study focuses on NIOSH's activities since the mid-1990s in the development of the CPDM. These efforts built on decades of prior NIOSH work, including research on the risk of exposure to respirable coal mine dust and health surveillance of coal miners in the United States. Additional NIOSH efforts have focused on improving dust control technologies in coal mines, such as dust collection, ventilation, and water spray systems (Colinet et al., 2010).

Early Regulation of Coal Mines

In 1968, a coal mine explosion in Farmington, West Virginia, killed 78 miners and was a major impetus for legislative action by the federal government. This led to the passage of the Federal Coal Mine Health and Safety Act of 1969 ("the Coal Act") (Public Law 91-173, December 30, 1969), which established the Mining Enforcement and Safety Administration within the Department of the Interior. The Coal Act established a mandatory federal exposure limit for the average concentration of respirable dust in underground coal mines of 3.0 mg/m^3 of air, which was subsequently lowered to 2.0 mg/m^3 after 1972. The Coal Act also mandated regular inspections at underground and surface mines as well as the use of personal gravimetric dust samplers, a sampling technology developed by the U.S. Bureau of Mines (Schlick and Peluso, 1970).

The Federal Mine Safety and Health Act of 1977 ("the Mine Act") amended the Coal Act, consolidating all federal health and safety regulations for the mining industry under a single statutory authority. The Mine Act transferred responsibility for carrying out its mandates from the Department of the Interior to the Department of Labor and established a new agency, MSHA. Additionally, the Mine Act established the Federal Mine Safety and Health Review Commission to provide independent review of the majority of MSHA's enforcement actions. This legislation still governs MSHA's activities.

MSHA promulgated respirable dust standards implementing section 202(b) of the Mine Act. These standards established that coal mine operators must continuously maintain the average concentration of respirable dust to which each miner is exposed during each shift at or below 2.0 mg/m^3 of air. The Mine Act also gives Part 90 miners, those who already have sufficient evidence of CWP, the legal option to request to work in a low-dust area of the mine.

In 1995, NIOSH published a criteria document based on its research on the relationship between coal dust exposure, type of coal, and the incidence of CWP (NIOSH, 1995). The report proposed reducing the recommended exposure limit (REL) from 2.0 to 1.0 mg/m^3 to reduce the adverse effects of exposure to respirable coal mine dust. It also recommended (1) keeping worker exposures as far below the REL as feasible through the use of engineering controls and work practices; (2) frequent monitoring of worker exposures; and (3) participation of miners in the recommended medical screening and surveillance program.

NIOSH's Health Surveillance of Coal Workers

The Coal Act also established the CWHSP. Since its creation in 1970, NIOSH has administered the CWHSP in monitoring the prevalence of CWP. Under the CWHSP, NIOSH provides periodic X-ray examinations for miners through the Coal Workers' X-ray Surveillance Program. In March 2006, NIOSH launched the ECWHSP to increase participation by providing additional respiratory health evaluations to coal miners (NIOSH, 2018c). This program offers lung function testing in addition to chest X-rays as part of the medical examination and asks miners to fill out occupational and health surveys. The ECWHSP uses a mobile medical examination unit to bring the medical exams to miners in the field and provide early detection of dust-related pulmonary disease, as well as target additional areas for prevention. Both surveillance programs are provided at no cost to miners, but participation is voluntary.

Through the CWHSP, NIOSH observed an increase in the prevalence of CWP in the mid-2000s as well as more cases of the disease showing up in younger miners in the United States (NIOSH, 2008). Recent data show that now more than 10 percent of miners examined with 25 or more years of tenure have been diagnosed with CWP (Blackley, Halldin, and Laney, 2018). Furthermore, NIOSH research found that coal miners with CWP are dying at a more rapid rate than in the past—between 1996 and 2016 the average number of years of potential life lost (YPLL) due to CWP increased from 8.1 to 12.6 (Mazurek et al., 2018). The increasing severity and rapid progression of CWP among coal miners has coincided with an 8.6-fold increase in the prevalence of PMF, an aggressive form of CWP, from an annual average of 0.37 percent in the mid-1990s to 3.23 percent from 2008 to 2012.

Activities Relating to the Development of Personal Dust Monitors

Table 2.1 provides a timeline of the key NIOSH activities and the related events covered in this case study. Note that the table includes only those events covered in the economic analysis. However, in the text that follows, we describe other events that predate the case study. Also, note that the analysis of benefits extends beyond the time period represented in the table.

Table 2.1. Key NIOSH Activities and Related Events: Personal Dust Monitor Case Study

Year or Period	Event or Activity
1992	At the direction of the U.S. Secretary of Labor, an MSHA interagency task group conducted a review of the coal mine respirable dust control program and recommended accelerating the development of a fixed-site continuous dust monitor and a CPDM.
1995	NIOSH issued a criteria document proposing a reduction of the REL for respirable coal mine dust from 2.0 to 1.0 mg/m^3. It also recommended better work practices and use of engineering controls, frequent monitoring of worker exposure, and worker health screenings.
1995–1996	NIOSH and R&P developed and tested prototypes of a fixed-site machine mountable continuous respirable dust monitor (MMCRDM). In 1999, NIOSH discontinued its development.
1996	The Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers issued a report recommending reducing the permissible exposure limit (PEL) for respirable coal mine dust, carrying out additional compliance sampling with emphasis on the use of personal monitoring, and using continuous dust monitors once the technology became available.
1998–early 2000s	NIOSH awarded a contract to R&P to develop prototypes of a wearable CPDM for coal miners. NIOSH collaborated in an informal partnership with industry, labor, and MSHA to develop and test the prototype devices in laboratory and mine settings.
2004–2008	NIOSH published two reports demonstrating the CPDM provided accurate readings of a miner's dust exposure and was wearable and durable during mine testing. In 2008, NIOSH published a report demonstrating the equivalency of the CPDM to the gravimetric sampler and establishing that the new instrument could be used for compliance sampling.
2009	NIOSH and MSHA certified the first commercial CPDM (Thermo Fisher Scientific PDM 3600) for use in underground and surface coal mines.
2010	MSHA proposed a rule reducing the PEL for respirable coal mine dust and requiring the use of CPDMs for high-risk underground coal mine occupations. NIOSH and Thermo Fisher Scientific (formerly R&P) conducted regional workshops and visited mines to demonstrate the CPDM.
2014	MSHA issued the final coal mine dust rule. NIOSH and MSHA certified a modified version of the CPDM (Thermo Fisher Scientific PDM 3700), which was widely adopted in response to the new regulation.
2016	In February 2016, mine operators were required to begin sampling high risk occupations using CPDMs. In August 2016, the PEL for respirable coal mine dust was lowered from 2.0 to 1.5 mg/m^3 for underground and surface mine workers and from 1.0 to 0.5 mg/m^3 for Part 90 miners.

Two government reports in the 1990s recommended the research and development of improved technologies for monitoring exposure to respirable coal mine dust. In May 1991, Secretary of Labor Lynn Martin directed MSHA to conduct a thorough review of the program to control respirable coal mine dust and to develop recommendations for how the program could be improved following findings of suspected widespread tampering with dust samples by mine operators at nearly 850 underground coal mines. In response, MSHA established an interagency task group. The 1992 Report of the Coal Mine Respirable Dust Task Group included a recommendation "for the accelerated development of two coal mine dust monitors: (1) a fixed-site monitor capable of providing continuous information on dust levels to the miner, mine operator, and to MSHA, if necessary, and (2) a personal sampling device capable of providing both a short-term personal exposure measurement as well as a full-shift measurement" (Cantrell et al., 1996, p. 91).

A second report issued in 1996 by the Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers recommended that MSHA should consider lowering the PEL for coal mine dust (MSHA, 1996). The advisory committee also recommended MSHA should carry out additional compliance sampling and place emphasis on the use of personal monitoring for determining compliance with PELs. In addition, the advisory committee recommended MSHA should conduct research in consultation with other agencies such as NIOSH on continuous dust monitors—and once the technology has been verified, to use these monitors in conjunction with other sampling methods for surveillance.

In response to the first report, NIOSH's Pittsburgh Research Center (PRC) initiated the development of a fixed-site MMCRDM (Cantrell et al., 1996). This instrument was the first application of the R&P tapered element oscillating microbalance (TEOM) sensor specifically designed for mine use. MMCRDM prototypes were developed and evaluated in underground coal mines in 1995 and 1996 (NIOSH, 1997). However, due to concerns about the instrument's accuracy, which could not be validated in mine tests, and the lack of comparability of fixed-site versus personal sampling, in 1999 NIOSH discontinued development of the MMCRDM.

In 1998, NIOSH's PRC issued a request for proposal to develop a wearable one-piece personal dust monitor using a mass-based sensor to measure respirable coal mine dust.[3] A research contract was awarded to R&P (valued at approximately $2.2 million in 1998) to miniaturize and electronically stabilize the TEOM technology to make it wearable. NIOSH, through an informal partnership with the Bituminous Coal Operators Association, National Mining Association, and United Mine Workers of America, collaborated in product development, and with support from MSHA conducted laboratory and field testing of prototype devices in the early 2000s. During the development stage between about 2003 and 2006, NIOSH brought about a dozen devices to mine operators to conduct workshops demonstrating the instrument to miners. NIOSH left the devices for a short period of time for miners to continue to test them, and then returned to see the data. One of NIOSH's goals was for the mines to see the devices as valuable in protecting worker health.

NIOSH published two reports in 2004 and 2006 finding the prototypes provided accurate readings of a miner's dust exposure and were wearable and durable during mine testing (NIOSH, 2004, 2006). NIOSH testing showed that the accuracy of the CPDM was equivalent to the gravimetric sampler—demonstrating that previous health findings were applicable to measurements taken with the CPDM and establishing that the new instrument could be used for compliance sampling (Page et al., 2008). The device was the first major advance in dust sampling technology in more than 30 years. It provided continuous exposure information not

[3] Previous NIOSH research evaluating different technologies (e.g., beta attenuation, light scattering) suggested that mass-based measurement is the most feasible and accurate for the underground mining environment.

previously available to coal miners and coal mine operators—and had the advantage of providing a direct end-of-shift reading.

Evidence of Adoption

The first commercial CPDM (the PDM 3600) was introduced by Thermo Fisher Scientific (formerly R&P) in 2009.[4] NIOSH and Thermo Fisher Scientific conducted regional workshops in 2010 to help coal miners learn how to use the new instrument. NIOSH awarded another contract to Thermo Fisher Scientific in 2012 to revise the design and make the device lighter to carry. A modified version, the PDM 3700, was developed and certified by MSHA and NIOSH in December 2014. After the PDM 3700 was certified, NIOSH in collaboration with MSHA conducted another round of workshops in 2015. Thermo Fisher Scientific independently led its own workshops demonstrating the new instrument. Between December 2014 and early 2018, about 2,300 units were sold.

In 2014, MSHA published a final rule requiring the use of CPDMs for occupations at high risk of exposure to excessively high concentrations or respirable coal mine dust. Underground mine operators widely adopted CPDMs in anticipation of the final rule when the new sampling requirements for certain occupations went into effect in February 2016.

Development of the Coal Mine Dust Rule

In 2010, MSHA issued the proposed rule "Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors" (MSHA, 2010). MSHA cited NIOSH's research as an important factor motivating a reduction in the PEL and requiring the use of CPDMs. The final rule was promulgated on May 1, 2014 (MSHA, 2014b). The rule revised existing standards and mandated several new requirements, including:

- lowering the existing PELs for respirable coal mine dust
- requiring the use of CPDMs
- redefining the term "normal production" shift to require that underground mine operators sample when production is at least 80 percent of the average production over the last 30 production shifts[5]
- requiring full-shift sampling
- requiring immediate corrective actions once a single, full-shift sample resulted in an excessive concentration measurement

[4] In April 2005, R&P was acquired by Thermo Electron, which merged with Fisher Scientific in 2006 to become Thermo Fisher Scientific.

[5] Under the previous definition, mine operators were required to sample when production levels were at least 50 percent of the average production reported during the last sampling period (i.e., the last set of five valid samples).

- allowing MSHA inspectors to use single, full-shift samples to determine compliance
- expanding medical surveillance requirements
- establishing training and certification requirements for workers who perform sampling and who maintain and calibrate sampling equipment.

Beginning on February 1, 2016, mine operators were required to begin collecting dust samples using CPDMs for certain designated occupations and other designated occupations in underground mines, and for all Part 90 miners. Many underground mines conducted sampling in January 2016 using gravimetric samplers to comply with the previous bimonthly sampling requirement and began quarterly sampling with CPDMs in April 2016. In August 2016, MSHA lowered the PEL for respirable coal mine dust from 2.0 mg/m^3 to 1.5 mg/m^3 of air for underground and surface coal mines, and from 1.0 mg/m^3 to 0.5 mg/m^3 for intake air at underground mines and for Part 90 miners.

Early Impacts of Adoption

The CPDM produces a dust data card and data file using end-of-shift measurements that provide a time record of dust exposure, so miners can see when concentrations were higher during their work shift.[6] The dust data cards must be posted or shared with workers within 12 hours or before the next work shift. When they are combined with operational information provided by miners shortly after their shift, potential dust sources can be evaluated. Based on visits to six mines during 2016 and 2017, NIOSH researchers found that, in response to reviewing this information, miners identified higher dust concentrations at various times and attributed increases in exposure to specific activities—something they were not previously able to do using gravimetric samplers (Haas and Colinet, 2018). NIOSH further noted that miners paid increased attention to problems identified in mine ventilation plans, resulting in improved responsiveness to these issues. NIOSH also found that miners took several corrective actions in response to excessively high coal dust measurements after using the CPDM. Table 2.2 provides examples of these activities and associated corrective actions.

[6] The dust card provides a 30-minute concentration and a cumulative mass concentration measurement.

Table 2.2. Mining Activities Linked Increases in Exposure and Corrective Actions Following the Adoption of CPDMs

Occupation	Activities to Which Increases in Exposure Were Attributed	Corrective Actions
Continuous miner operator	• Working close to areas after rock dusting • Tramming, repositioning (e.g., turning a crosscut), or moving a continuous mining machine • Carrying coal by conveyor up the tail boom of the miner to be loaded into shuttle cars	• Advancing the ventilation curtain toward the face for exhaust face ventilation or standing in intake air at the curtain discharge (when safe in terms of visibility) when using blowing face ventilation • Stepping further back from the face or turning their body away from the miner while cutting • Proceeding with certain work practices—specifically, lowering the cutting boom—at a much slower pace to minimize stirring up excessive dust • Using best practices to reduce personal or environmental exposure, such as using a wash-down hose to clean material away from water spray manifolds during otherwise idle time
Roof bolter	• Drilling, during the initial phase, until the drill bit is completely contained within the hole • Drilling while downwind of the continuous mining machine due to the additional dust being generated	• Drilling the initial few inches much slower • Keeping upwind of the continuous miner • When possible, bolting the face furthest away when downwind of the continuous miner • Staying out of the return air when not bolting • Alternating changing of dust collection bags so that one person is not getting all of this specific unavoidable dust exposure
Other occupations	• Rock dusting • Excessive dust releases during longwall mining	• Rock dusting more between shifts to avoid exposing miners during their working shift • Watering down areas to prevent dust liberation (e.g., using water and shield sprays on the longwall shearer)

SOURCE: Haas and Colinet, 2018.

Mine operators also stated that CPDMs allowed them to identify elevated periods in dust concentrations that were previously not observable. For example, mine operators noted that they observed spikes in exposure while using rubber-tired equipment to transport miners in and out of the mine. Having a time record allowed miners to take corrective actions to further reduce exposures, such as increasing the distance between vehicles entering the mine.

Approach for Estimating the Economic Benefit of Personal Dust Monitors

Having described NIOSH's activities and documented their likely role in reducing exposure to respirable coal mine dust, we now present our analysis of the estimated monetary value of those impacts. To do this, we use the following steps: (1) identify the target population; (2) estimate the number of workers affected; (3) estimate the reduction in exposure; (4) estimate the number of avoided illnesses and fatalities; and (5) monetize those avoided illnesses and fatalities.

The analysis presented in this case study represents the benefits associated with the development, testing, and eventual widespread adoption of CPDMs in underground coal mines relative to a baseline *in which no other organization or entity brought about similar changes*. This assumption is predicated on the fact that only one personal dust monitor has been certified by NIOSH and MSHA for use in underground mines in the United States—and while this technology has been in development over the last two decades, no comparable devices have been developed in other parts of the world where coal mining is prevalent. The challenge in this case study in terms of attribution to NIOSH is the fact that the MSHA coal mine dust rule mandated several changes to existing standards, some of which were related to CPDM use and some of which would likely have been promulgated even in the absence of the new technology, such as the mandatory reduction in the PEL. While this does not detract from NIOSH's contribution—it merely demonstrates that the CPDM was an important pillar of a multipronged approach to reducing exposure to respirable coal mine dust—it makes it challenging to separately analyze and attribute benefits to individual components of the new regulatory regime.

To measure the benefits of NIOSH's technological contribution to reducing the risk of exposure to high concentrations of respirable coal mine dust, we compare the reduction in negative health outcomes associated with observed reductions in exposure levels and *the reduction in health outcomes that might have occurred in an alternative scenario without NIOSH*. In this alternative scenario, we assumed that research and development funded by NIOSH did not occur and that while awareness of the risk of exposure to respirable coal mine dust and subsequent regulation occurred in some form, coal miners did not have the benefit of access to real-time and end-of-shift dust concentration measurements from which they could take actions in response and adjust their work practices. Furthermore, in a world without NIOSH, we assume no other organization would substantially invest in the engineering and design concepts to develop a personal dust monitor.

To assess the effect on exposures associated with NIOSH's contribution, we estimate the reduction in the average concentration of respirable coal mine dust over the six-month period from February 2016 to July 2016, during which mine operators were first required to conduct compliance sampling using CPDMs under the final coal mine dust rule (the additional requirements reducing the PEL for respirable coal mine dust went into effect in August 2016). This time period represents an observable counterfactual, an alternative state of the world in which the implementation of CPDMs was the only intervention, thus helping to differentiate the impact of NIOSH's contribution to the development and adoption of CPDMs from the impacts of additional requirements associated with the MSHA rulemaking. MSHA's regulatory analysis in support of the final coal mine dust rule quantified the benefits from three major provisions of the rule: reducing the PEL, basing determinations of noncompliance on MSHA inspector single samples, and revising the definition of a normal production shift. However, MSHA's analysis did not separately attempt to quantify the benefits of the adoption of the new personal dust sampling technology.

We present our results for each of the five steps in the rest of this section.

Step 1: Identify the Target Population

The focus of this case study is NIOSH's role in the adoption of CPDMs, therefore the primary target population is coal miners benefiting from their use. In 2015 there were 1,460 active coal mines in the United States: 405 underground coal mines and 1,055 surface coal mines (NIOSH, 2015). These mines employed an average of 98,505 miners and contractors during the year, excluding office workers: 47,794 at underground mines and 50,711 at surface mines (MSHA, undated).

Step 2: Estimate the Number of Affected Workers

This step includes a discussion of exposure levels, but primarily focuses on allocating the affected mining population into categories that will later be used as the framework for estimating changes in exposure. Not all miners are exposed to high concentrations of respirable coal mine dust. In the regulatory analysis for the coal mine dust rule, MSHA estimated that 31,339 underground coal miners and 30,504 surface coal miners (about 60 percent of the labor force) are directly involved in or in the vicinity of operations that generate respirable coal mine dust (MSHA, 2014a). In addition, MSHA estimated that fewer than 100 Part 90 miners may be at risk of exposure to excessively high dust concentrations. However, health screening is voluntary, so there may be additional miners with CWP who do not have a formal diagnosis and are potentially eligible for Part 90 status. NIOSH has found that over the last 30 years only 14.4 percent of eligible miners exercised their Part 90 option to transfer to a less dusty job in the mine (Reynolds et al., 2018). The MSHA rule only required underground miners and Part 90 miners to use CDPMs; these groups are the focus of this study as there has been very limited adoption of CPDMs at surface mines.

We estimate the number of workers and their average exposure levels by occupation to account for differences in work practices and conditions in measuring the impact of CPDMs. Information is available on the number of miners in each occupation. We also need to estimate the distribution of workers by coal rank (i.e., a measure of the coal's moisture and carbon content) and recurrency (i.e., how frequently coal dust measurements exceed 2.0 mg/m^3 or 1.0 mg/m^3) within each occupation since the exposure risk models we rely on use these factors to estimate the excess risk of respiratory disease due to occupational exposures. Each coal dust sample is associated with an occupation and a work location (WL). Since we do not know the exact distribution of workers, we use the distribution of WLs to allocate workers in each occupation into coal rank and recurrency categories. In a 2003 proposed rule for compliance sampling for respirable dust, MSHA based its risk assessment on underground WLs exhibiting a "pattern of recurrent overexposures" (MSHA, 2003, p. 10825). MSHA's *Quantitative Risk Assessment in Support of the Final Respirable Coal Mine Dust Rule* (QRA) defined three mutually exclusive "recurrency classes" to categorize WLs based on inspector and operator samples (MSHA, 2013). We define a WL as specific work area within a single mine for a particular occupation. We classify 9,998 different WLs according to coal rank and recurrency.[7] The combination of these factors describes environmental conditions that present similar health risks to miners. Since we only observe the percentage of WLs that fall into each category, we assume that these percentages are equivalent to the share of miners within an occupation working in similar conditions. While we do not have sufficiently detailed information to identify coal rank for each individual mine in MSHA's Mines dataset, we use the distribution of WLs by coal rank within each occupation from MSHA's QRA (MSHA, 2013).[8] To estimate the distribution of WLs across recurrency classes, we multiply the total number of WLs within each occupation by the average percentage of WLs in each recurrency class across all years. Using data from MSHA's Coal Dust Samples dataset, we categorize WLs for underground workers and Part 90 miners into the following recurrency classes:

- **High-recurrence:** Any WLs with a least two valid samples exceeding 2.0 mg/m^3 (or 1.0 mg/m^3 for Part 90 miners) for the same occupation. Of the 9,998 WLs sampled, 523 or 5.2 percent, fall into this category.
- **Mid-recurrence:** Any WLs, not including those in high-recurrence areas, with at least two valid samples for the same occupation exceeding 1.0 mg/m^3 (or 0.5 mg/m^3 for Part 90 miners); 1,772 WLs or 17.7 percent fall into this category.
- **Low-recurrence:** Any WLs with no more than one valid sample for the same occupation exceeding 1.0 mg/m^3 (or 0.5 mg/m^3 for Part 90 miners); 7,703 WLs or 77.0 percent fall into this category.

Table 2.3 reports the number of workers at risk of exposure to excessively high concentrations of coal mine dust. Part 90 miners and most underground coal miners are now required to use CPDMs. Surface coal miners, apart from Part 90 miners, are not required to use CPDMs but may voluntarily choose to adopt them for compliance sampling. We estimate the impact of CPDMs for all high-risk occupations regardless of the specific sampling requirements for each job category, because some occupations will use CPDMs more frequently than others and some occupations will continue to be sampled primarily during MSHA inspections. We do not estimate impacts for other non-"high-risk" occupations or surface miners, which are not shown in the table.

[7] We include WLs with samples taken from 2010 to 2015 and determine the recurrency class for each WL separately each year. We then calculate the average percentage of WLs within each occupation that fall into each recurrency class across all years.

[8] This distribution is taken from Table 27 of MSHA's QRA. MSHA uses the coal rank definition from the *Dictionary of Mining, Mineral and Related Terms*, which states: "High-rank coals are defined as coals containing less than 4 percent of moisture in the airdried coal or more than 84 percent of carbon (dry ash-free coal). All other coals are considered as low-rank coals." We include three categories: low-/medium-rank, high-rank bituminous, and anthracite coal, which is the highest-rank coal.

Table 2.3. Estimated Number of Affected Workers, by Occupation, Recurrency Class, and Coal Rank

	Low-Recurrence			Mid-Recurrence			High-Recurrence			
Occupation	**Low-/Med.-Rank**	**High-Rank Bituminous**	**Anthracite**	**Low-/Med.-Rank**	**High-Rank Bituminous**	**Anthracite**	**Low-/Med.-Rank**	**High-Rank Bituminous**	**Anthracite**	**Total**
Auger Operator	1	1	0	4	2	0	1	1	0	**10**
Continuous Miner Operator	244	339	2	485	675	3	232	323	2	**2,305**
Cutting Machine Operator	2	6	0	3	8	0	2	5	0	**26**
Drill Operator	7	20	0	0	1	0	0	0	0	**28**
Electrician and Helper	1,321	2,137	14	1	2	0	0	0	0	**3,474**
Laborer	466	1,183	591	8	21	10	2	4	2	**2,287**
Loading Machine Operator	37	270	0	0	0	0	0	0	0	**307**
Longwall Headgate Operator	53	86	0	42	67	0	2	3	0	**253**
Longwall Jacksetter	74	118	0	56	90	0	18	29	0	**386**
Longwall Tailgate Operator	8	12	0	29	47	0	14	23	0	**133**
Mechanic and Helper	301	499	24	2	4	0	0	0	0	**830**
Mobile Bridge Operator	184	434	7	72	171	3	9	20	0	**900**
Roof Bolter	1,678	2,467	8	518	762	3	46	68	0	**5,550**
Scoop Car Operator	806	1,118	0	34	47	0	2	2	0	**2,009**
Section Foreman	895	842	108	9	8	1	1	1	0	**1,866**
Shuttle Car Operator	1,773	2,342	8	377	498	2	23	30	0	**5,053**
Uni-Hauler Operator	44	137	11	1	4	0	0	0	0	**198**
Utility Man	289	312	0	6	6	0	0	0	0	**613**
All Other Underground Jobs	1,575	2,905	271	80	147	14	40	74	7	**5,111**
Part 90 Miners	17	23	0	8	11	0	3	4	0	**66**
Total	**9,774**	**15,250**	**1,044**	**1,736**	**2,570**	**36**	**396**	**588**	**11**	**31,405**

SOURCE: Total employment figures based on MSHA, 2014a. Estimated distribution of workers across WLs based on RAND analysis of MSHA's Coal Dust Samples dataset
NOTE: All groups listed in this table are underground miners, with the exception of Part 90 miners, some of whom work in surface mines. Part 90 miners are excluded from the other job categories. Totals may not sum precisely due to rounding.

Step 3: Estimate the Reduction in Exposure

To estimate the reduction in the average concentration of respirable coal mine dust, we use data from MSHA's Coal Dust Samples dataset, which is comprised of inspector and operator dust samples (MSHA, 2019a).[9] Both inspector and operator samples taken before February 1, 2016, were collected using gravimetric samplers, labeled as coal mine dust personal sampler units (CMDPSUs). After February 1, 2016, the coal mine dust rule required operator samples for Part 90 miners and underground miners in high-risk occupations to be collected using CPDMs. During mine inspections, MSHA inspectors continue to use CMDPSUs because only approved gravimetric samplers can be used to collect samples suitable for crystalline silica (quartz) analysis—silica in coal dust contributes to pneumoconiosis in coal miners. Inspectors also want to mimic mine conditions during nonsampling shifts on typical production days. Therefore, we look at samples collected in the years before and after the implementation of the coal mine dust rule to estimate the impact of using CPDMs. The implementation of the rule over several stages resulted in three distinct periods:

1. Prior to February 2016, operator samples were collected using the CMDPSU, and the PEL was 2.0 mg/m^3 of air (1.0 mg/m^3 for Part 90 miners).
2. From February 2016 through July 2016, operator samples were collected using the CPDM, and the PEL was 2.0 mg/m^3 of air (1.0 mg/m^3 for Part 90 miners).
3. From August 2016 to December 2018, operator samples were collected using the CPDM, and the PEL was 1.5 mg/m^3 of air (0.5 mg/m^3 of air for Part 90 miners).

Between 2010 and 2018, about 981,000 inspector and operator samples were collected. Approximately 184,000 of these samples were voided for various reasons (e.g., cassette not received, contaminated, insufficient dust observed, invalid work shift, etc.). We also excluded samples that could not be linked to an occupational exposure.[10] Finally, we excluded operator samples taken after abatement measures and MSHA inspector samples taken within 21 days of a previous inspection. In both cases, these samples were generally follow-up samples collected in response to excessively high dust concentration measurements taken during a previous sample. MSHA conducted a statistical analysis of these follow-up samples and found they were systematically different from the initial (i.e., not follow-up) samples collected (MSHA, 2013). Therefore, MSHA determined that follow-up samples were less likely to be representative of

[9] Data have been collected since January 1, 2000, and are updated on a weekly basis.

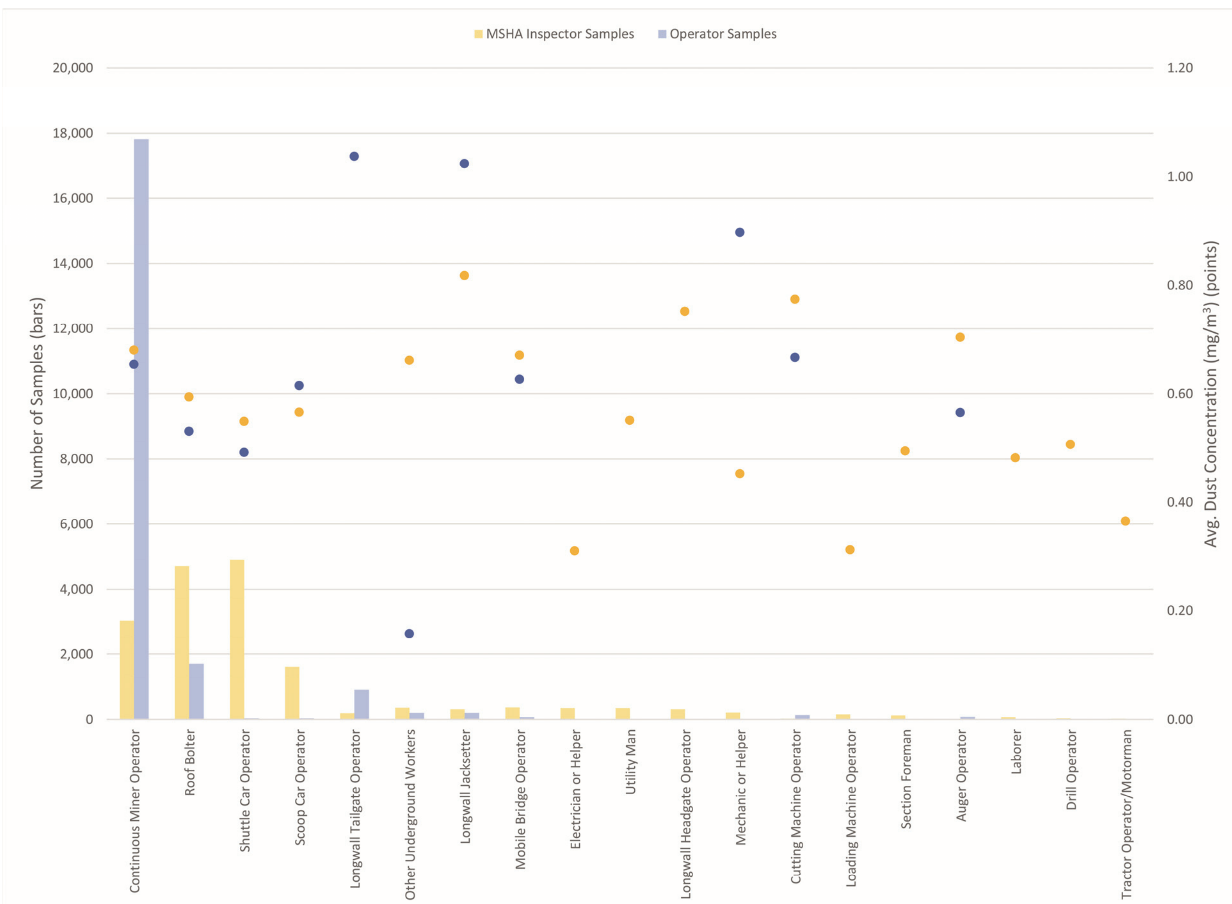
[10] Roof bolter, similar to other occupations, has several associated occupational codes. In this category we also include underground designated area samples for which the job code is missing and the first digit of the entity code is 9, which indicates it is a roof bolter sample.

average dust concentration levels. Thus, to obtain a representative sample of average dust concentration measurements, we excluded the following:

- voided samples
- invalid, control, or intake air samples
- invalid or unknown occupation codes (not excluding roof bolters, who are identified by work area)
- dust concentration of zero (or less)
- extreme outliers (i.e., dust concentration > 15 mg/m^3 of air)
- operator samples after abatement measures or MSHA reinspection samples.

To illustrate the coal mine dust sample data after this initial step, Figure 2.1 reports the number and average dust concentration of the underground mine inspector and operator samples in 2014, the year MSHA's final coal mine dust rule was promulgated. Collecting operator samples is only required for certain high-risk occupations in underground mines. The most

Figure 2.1. Coal Mine Dust Samples for Underground Miners by Occupation, 2014



SOURCE: RAND analysis of MSHA's Coal Dust Samples dataset.

frequently sampled occupations are continuous miner operator and roof bolter—these two occupations account for approximately 25 percent of affected workers, as shown in Table 2.3. For several occupations, no operator samples are collected (i.e., there are no compliance sampling requirements); however, MSHA inspectors sample these occupations during mine inspections. Prior to 2016, operator samples accounted for slightly more than half of all samples collected, but due to increased sampling requirements operator samples now account for more than 80 percent of all samples collected.

Estimating the Baseline Average Respirable Dust Concentration

To estimate the average baseline dust concentration (i.e., prior to the adoption of CPDMs) we rely on a combination of inspector and operator samples from 2010 to 2015 for high-risk occupations. In MSHA's assessment, inspector samples are more likely representative of typical exposure levels than operator samples because there is less likelihood of selection bias due to the choice of the sampling days as MSHA inspections are unannounced and independently scheduled. In addition, inspector samples cover a wider range of occupations than operator samples. However, since there are fewer routine samples by MSHA inspectors for certain high-risk occupations, we also supplement the inspector samples for less frequently sampled occupations with operator samples.

We rely on a bias correction method proposed by MSHA to estimate average baseline exposure levels, which MSHA refers to as "adjusted, supplemental estimates." The derivation of these estimates is described mathematically in Appendix F of MSHA's QRA (MSHA, 2013). We summarize it here in less detail. Where available, we primarily rely on MSHA inspector samples for the baseline estimates. However, we use the combined average measurements of inspector samples and operator samples when there are less than two samples per WL (defined as a specific work area in a single mine) for an occupation, or when the average dust concentrations of operator samples are higher than inspector samples to account for potential bias when inspector samples are collected on lower production days, for example. We also apply an adjustment factor (i.e., increase) the average dust concentration estimates where the average of operator samples exceeding 1.0 mg/m^3 (or 0.5 mg/m^3 for Part 90 miners) is greater than for the combination of operator and inspector samples exceeding this limit for each WL and job title.

Table 2.4 reports the baseline average concentration of respirable coal mine dust by occupation and recurrency class. We did not have detailed information on coal rank for each mine; therefore, we assume that average exposure levels are similar between low- and high-rank coal mines. MSHA's analysis suggests that for most occupations average dust concentrations are not significantly different between low- and high-rank mines (see Table 12 of MSHA's QRA).

Table 2.4. Average Concentration of Respirable Coal Mine Dust for Underground Miners and Part 90 Miners by Occupation and Recurrency Class, 2010–2015

Occupation	Low-Recurrence	Mid-Recurrence	High-Recurrence
Auger Operator	0.645	0.802	1.527
Continuous Miner Operator	0.525	0.816	1.126
Cutting Machine Operator	0.572	0.906	1.270
Drill Operator	0.482	1.056	–
Electrician and Helper	0.342	0.785	–
Laborer	0.418	1.518	1.781
Loading Machine Operator	0.317	–	–
Longwall Headgate Operator	0.637	0.938	1.341
Longwall Jacksetter	0.685	1.061	1.497
Longwall Tailgate Operator	0.849	1.093	1.444
Mechanic and Helper	0.414	1.009	–
Mobile Bridge Operator	0.527	0.913	0.969
Roof Bolter	0.502	0.886	1.218
Scoop Car Operator	0.530	1.168	1.658
Section Foreman	0.467	1.614	2.839
Shuttle Car Operator	0.440	0.939	1.390
Uni-Hauler Operator	0.403	1.223	–
Utility Man	0.520	1.288	–
All Other Underground Jobs	0.552	1.315	2.660
Part 90 Miners	0.200	0.475	0.708

SOURCE: RAND analysis of MSHA's Coal Dust Samples dataset.
NOTES: Part 90 miners are excluded from other job categories.
"–" indicates no WLs were sampled.

Estimating the Impact of Personal Dust Monitors

This analysis estimates the change in average dust concentration for certain high-risk occupations after the adoption of CPDMs. There are three primary mechanisms through which CPDMs can affect exposure to respirable coal mine dust: (1) cumulative real-time measurement, which allows workers to immediately adjust their position or adjust control technologies to reduce exposure to excessively high dust concentrations; (2) a dust data card with detailed 30-minute, end-of-shift measurements and a comma-separated values (CSV) data file that can be reviewed by mine operators and workers to identify activities contributing to higher dust concentrations and take corrective actions to mitigate them; and (3) a more tamper-resistant unit that improves the reliability of operator samples and incentivizes mine operators to take precautions to avoid excessive concentration measurements.

A significant impact of the adoption of CPDMs was a decline in the percentage of coal dust samples exceeding the PEL. Table 2.5 shows the percentage of samples exceeding the PEL during each of the time periods described earlier in Step 3. The two groups using CPDMs (underground miners and Part 90 miners) saw a significant reduction in excessive dust measurements in the six-month period after they began using the devices. There was essentially no change for surface workers who were not required to use CPDMs. After August 1, 2016, the PEL was reduced from 2.0 mg/m^3 to 1.5 mg/m^3 for underground and surface workers and from 1.0 mg/m^3 to 0.5 mg/m^3 for Part 90 miners. Given the implementation of the more stringent standard, unsurprisingly there was an increase in samples exceeding the PEL in the last period. However, the percentage of samples for both underground workers and Part 90 miners remained below levels before the adoption of the CPDM. This occurred despite the more stringent (and more frequent) sampling requirements—additional compliance sampling made it more difficult to underreport exposures by selectively sampling on lower production shifts/days because a higher number of valid samples was required for each calendar quarter.

Table 2.5. Number (and Percentage) of Coal Dust Samples Exceeding the PEL

Population	Jan. 1, 2010 to Jan. 31, 2016	Feb. 1, 2016 to July 31, 2016	Aug. 1, 2016 to Dec. 31, 2018
Surface workers	291	18	125
	(0.4%)	(0.3%)	(0.4%)
Underground workers	7,986	142	1,951
	(2.9%)	(0.4%)	(0.7%)
Part 90 miners	180	1	54
	(3.6%)	(0.2%)	(2.2%)

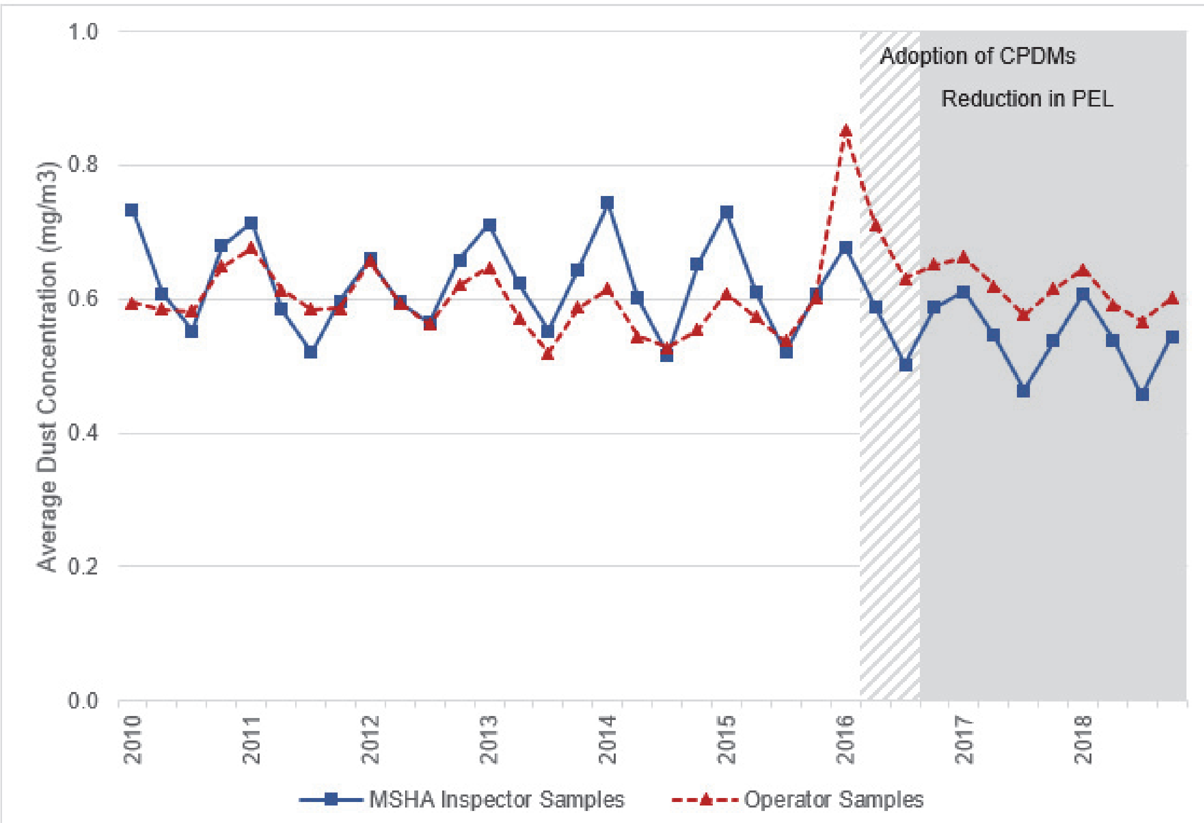
SOURCE: RAND analysis of MSHA's Coal Dust Samples dataset.

To estimate the impact of CPDMs on average dust concentration measurements, we use a before and after comparison for underground workers and Part 90 miners. We rely on inspector samples in MSHA's Coal Dust Samples dataset because they provide a more reliable estimate of average dust concentrations over time. Ideally, we would also use information from the operator samples collected by miners. However, based on findings of suspected tampering with dust samples by the Department of Labor and on NIOSH interviews with retired miners describing illicit actions to obtain lower dust concentration measurements,[11] it is likely that operator samples have a downward bias—particularly prior to 2016 when the gravimetric sampler was being used. As shown in Figure 2.1, average dust concentration measurements tend to be lower for operator samples than inspector samples for several high-risk occupations, such as continuous miner operators, cutting machine operators, roof bolters, shuttle car operators, and other underground workers.

[11] Examples of such actions that may result in downward bias of the operator samples include removing the cassette to intentionally void an otherwise valid high-concentration measurement, tampering with the filter to remove dust, hanging the device in a "clean" location, or passing the device to a different worker to wear.

Figure 2.2 shows the average dust concentration measurements of inspector samples and operator samples from 2010 to 2018. To facilitate direct comparison, we only include samples for continuous miner operators and roof bolters, which are the most frequently sampled occupations.[12] We combine data for these occupations to estimate the average dust concentration,

Figure 2.2. Average Respirable Coal Mine Dust Concentration (mg/m^3) for Underground Workers, Inspector and Operator Samples, 2010–2018



SOURCE: RAND analysis of MSHA's Coal Dust Samples dataset.
NOTE: Includes samples for continuous miner operators and roof bolters.

[12] One of the key limitations of the Coal Dust Samples dataset is it contains an unbalanced sample of occupations and work areas over time. Furthermore, samples are taken from a different distribution of mines and work areas each period—due to this inconsistency there is no discernable trend in the average dust concentration measurements for several occupations. This is particularly true for occupations that collect relatively few samples each period. For groups such as "other underground workers," the distribution of measurements varies considerably over time because it reflects a different mix of job titles and tasks each period. Furthermore, some high-risk occupations did not have to conduct compliance sampling prior to 2016 but were required to collect samples using CPDMs starting February 1, 2016. MSHA's coal mine dust rule also mandated a severalfold increase in the number of samples required.

first equally weighting samples by work area (rather than the number of samples collected) and then applying weights proportional to the number of workers in each occupation.

The average dust concentration measurements for inspector samples and operator samples are highly seasonal. Seasonal spikes in the data may be linked to humidity in the mine, which varies throughout the year and affects how dust binds and disperses. For several occupations, there was an increase in the average dust concentration measurements of operator samples after the adoption of CPDMs. Prior to 2016, operator samples for underground miners were generally lower than inspector samples. After 2016, this pattern was reversed; reported operator samples were both higher than they had previously been and higher than MSHA inspector samples in the same period. This counterintuitive finding suggests that exposures may have increased after workers began using CPDMs, but it also may be due to sample measurements becoming more representative of actual exposures.

One potential explanation for the increase is that underground workers in areas with lower dust levels began using cumulative real-time measurements at key decision points favoring actions that would increase exposures (e.g., taking an extra cut). Similarly, it is feasible that workers chose to work longer shifts or take other steps to increase coal production, such as working in more productive (and dusty) work areas. Several factors limit the plausibility of this explanation. First, 2016 was the lowest production year in the last 30 years (Energy Information Administration, 2018). If working longer shifts to increase production was widespread, we would expect to see an overall increase in production or a slowdown in the downward trend dating back to the previous peak in 2008.[13] Neither of these occurred. In contrast, in 2017 overall coal production increased by more than 6 percent, but average dust exposures decreased. Second, mine operators set production schedules weeks in advance and most coal miners work 10-hour shifts, 6 days a week (with two work shifts per day), so there are few additional hours in the day. Furthermore, in some cases, roof bolters noted that it was not easy to read the CPDM screen during their shift due to its location relative to their body position—therefore, it is unlikely they were able to continually monitor the device to make decisions to continue working.

An alternate explanation is that the data reflect a downward bias in the operator samples prior to 2016. In practice, while equivalent in accuracy to CMDPSUs, CPDMs led to the collection of significantly more reliable operator samples, which were less likely to underreport dust

[13] MSHA's Employment and Production dataset also shows that while a number of coal mines temporarily idled production or permanently closed between 2015 and 2016, the vast majority (approximately 80 percent) of mines that remained open had lower production levels in 2016 relative to the average of the previous five years.

concentration levels.[14] CMDPSUs are known to be vulnerable to tampering, although several improvements have been made since the 1990s. CPDMs were designed to be more tamper-resistant. For example, the data file that is transmitted to MSHA is encrypted. Furthermore, temperature and pressure data give clues about whether the device was used underground. With the introduction of CPDMs, the downward bias could be mitigated by more tamper-resistant equipment and more stringent sampling requirements under the MSHA rule. The structural shift in the operator sample measurements after 2016 makes it challenging to separately estimate the effect of CPDMs removing the downward bias (which would increase sample measurements) and miners taking corrective actions in response to CPDM readings (which would reduce sample measurements).

While CPDMs are only used in collecting operator samples, the effects, in terms of corrective actions taken to reduce exposures, are subsequently measured in both future operator *and* inspector samples. Specifically, the benefits of CPDMs do not only accrue on the days when they are being used, but on other days as well due to these corrective actions, such as miners adopting work practices that reduce exposures. Therefore, our subsequent analysis relies only on MSHA inspector samples. Inspector samples are generally a more reliable measure of average dust concentration and, as discussed here, capture the impacts of corrective actions taken in response to CPDM measurements. The limitation of this approach is that it may not be feasible to estimate the impact of cumulative real-time measurement during a single shift by a miner using a CPDM, which we describe as the first of three mechanisms through which CPDMs can affect exposures. This impact may be relatively small because miners do not wear CPDMs on a regular basis, only while collecting operator samples. For most designated occupations, 15 valid samples must be collected each quarter. Accounting for voided samples, an average of 20 to 25 samples may be taken on a quarterly basis for each designated occupation before CPDMs are passed along to the next designated occupation. Since there are two shifts per day, this implies that sampling using CPDMs may occur for as little as two to four weeks for a designated occupation during a calendar quarter. However, the benefits of lessons learned through end-of-shift measurements and adoption of better work practices as well as improvements in the reliability of operator samples will accrue to the working environment and not only when CPDMs are worn.

Figure 2.3 shows the average dust concentration measurements of inspector samples for a wider number of occupations because we are not limited by an insufficient number of operator

[14] Industry representatives noted that the initial temperature settings on the CPDM led to unreliable measurements; however, these samples were voided. Rather than anticipating the temperature of the mine environment in which the device will be located during the sampling shift as originally intended, some mine operators were instructed by the manufacturer to set the device at room temperature where the device is distributed (e.g., 72˚F) before entering the mine to obtain reliable measurements.

samples for several job categories.[15] However, we exclude certain occupations for which too few inspector samples are collected (i.e., less than a dozen samples in each quarter) or for which no samples were collected in certain years prior to 2016. MSHA inspectors conduct mine visits once per quarter at underground coal mining operations. To address sample size limitations, we chose this unit of time to provide a sufficient sample size for most occupations. We combine data for all included occupations to estimate the average dust concentration, first equally weighting samples by work area within each occupation (rather than the number of samples collected) and then applying weights proportional to the number of workers in each occupation. The figure shows that average dust exposure levels for underground workers were relatively stable from 2010 to early 2016, with a highly seasonal pattern. Average dust concentrations, including the peaks and troughs, then decreased starting in 2016 when quarterly sampling with CPDMs began. We note that the average dust concentration measurements for the first quarter of 2016 were lower than the first quarter measurements of the previous three years. However, mines were not required to adopt CPDMs until February 2016, and the vast majority of mines did not begin quarterly sampling with CPDMs until April that year.[16] While this is only one data point and there was a similar decline in the first quarter of 2012, it is plausible that a portion of this decline could be attributable to mine operators taking steps in anticipation of the new sampling requirements ahead of the implementation of MSHA's coal mine dust rule, including the use of CPDMs, to reduce exposures. Our time period of analysis does not align precisely with the interim regulatory period from February to July 2016 because we use quarterly and not monthly data due to sampling limitations and because most mines delayed the adoption of CPDMs until April 2016. Therefore, we use the second and third calendar quarters of 2016 to estimate the impact of CPDMs prior to the mandatory reduction in the PEL. We performed several robustness checks to determine the effect of using different specifications, such as including or excluding samples taken outside the defined time period between the adoption of CDPMs and the reduction in the PEL.

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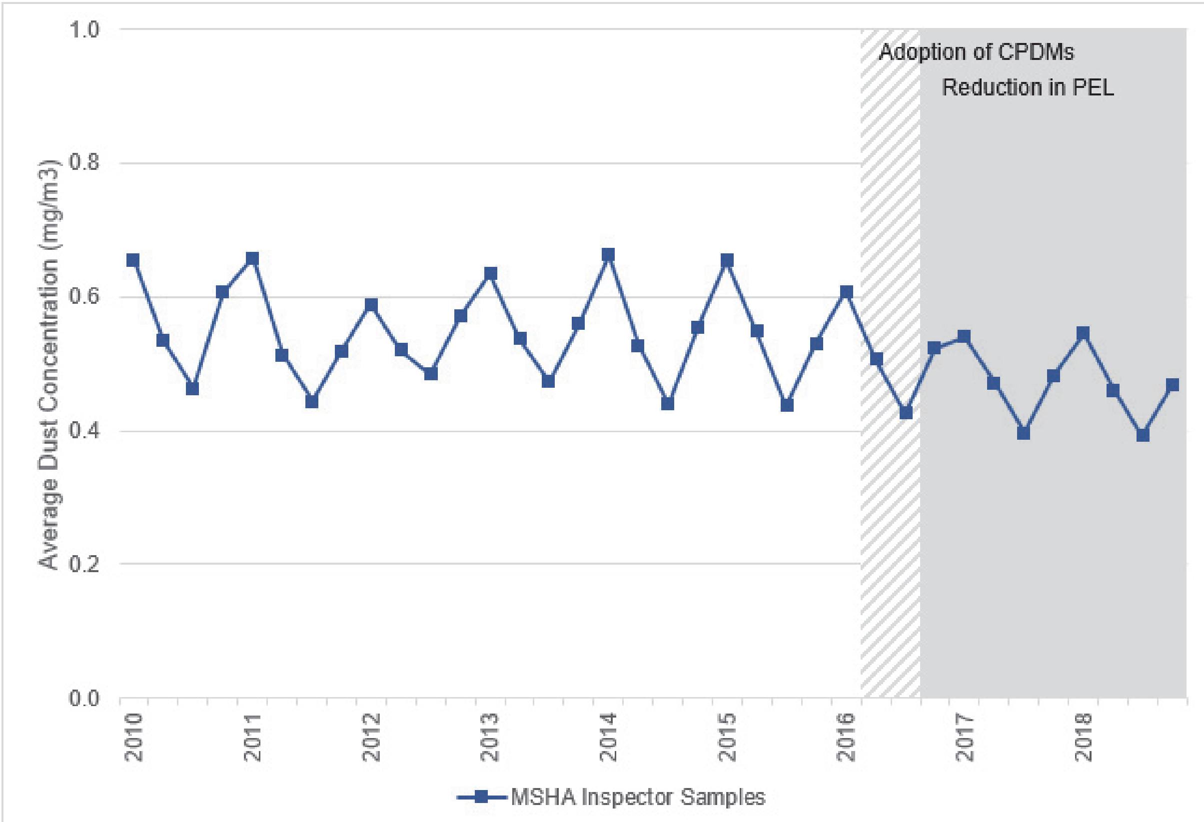
[15] These occupations include continuous miner operators, electricians or helpers, loading machine operators, longwall headgate operators, longwall jacksetters, longwall tailgate operators, mechanics or helpers, mobile bridge operators, roof bolters, scoop car operators, shuttle car operators, utility men, and Part 90 miners.

[16] MSHA data show that less than 20 mines submitted valid samples using CPDMs during the first quarter of 2016, and no mines submitted more than 15 valid samples using CPDMs.

Figure 2.3. Average Respirable Coal Mine Dust Concentration (mg/m^3) for Underground Workers, Inspector Samples, 2010–2018



SOURCE: RAND analysis of MSHA's Coal Dust Samples dataset.
NOTE: Includes inspector samples for continuous miner operators, electricians or helpers, loading machine operators, longwall headgate operators, longwall jacksetters, longwall tailgate operators, mechanics or helpers, mobile bridge operators, roof bolters, scoop car operators, shuttle car operators, utility men, and Part 90 miners.

During the first six months starting in February 2016, operator samples were required to be collected using CPDMs, but at the previously existing dust exposure limits. After July 2016, MSHA also mandated a reduction in the PEL for respirable coal mine dust. We are interested in measuring the impacts of these two requirements separately to assess their relative contributions. However, since there are relatively few months of data in which CPDMs were utilized without the more stringent exposure limits, it is challenging to say whether the first effect is measured with a high degree of precision (since the adoption of new technology can take much longer to achieve a desired efficacy) and whether it would have been the same had the latter policy not been mandated. For instance, miners may have continued to take corrective actions to further reduce exposures and the full impact would not have been realized for several additional months or years. However, we cannot say that the combined effect seen in the later period is entirely attributable to the CPDM. Nonetheless, the downward trend in the quarterly data after 2016 suggests that mine operators continued to take additional steps to reduce exposures in subsequent years. Furthermore, NIOSH researchers continued to observe mine operators taking corrective actions in response to using CPDMs (Haas and Colinet, 2018).

The before and after estimation is calculated as follows:

$$C_t = \alpha_0 + \beta_1 \delta_t^{PDM} + \beta_2 \delta_t^{PEL} + X_t + \varepsilon_t \qquad \textit{(Equation 1)}$$

where C_t is the average dust concentration at time t, α_0 is a constant, δ^{PDM} equals 1 if a sample is dated April 1, 2016, or later, δ^{PEL} equals 1 if a sample is dated October 1, 2016, or later, X_t is a vector of seasonal dummy variables (i.e., Q2, Q3, and Q4), and ε_t is a time-dependent error term. We conducted a test for stationarity and chose not to include a time trend because the estimated coefficient on the time trend was not statistically different from zero, and we could not reject the hypothesis that the pre-2016 samples exhibited a stationary process.[17] The coefficient on the first treatment, β_1, measures the incremental impact of adopting CPDMs. The coefficient on the second treatment, β_2, measures the incremental impact the reduction in the PEL. The combined coefficients, $\beta_1 + \beta_2$, measure the full impact of both requirements. We report the results in Table 2.6.

Table 2.6. Regression Estimate Measuring the Impact of Personal Dust Monitors and a Reduction in the Permissible Exposure Limit

	Coefficient
δ^{PDM}	–0.0296***
δ^{PEL}	–0.0417***
Q2	–0.0999***
Q3	–0.1738***
Q4	–0.0737***
Constant	0.6325***
Obs.	36
Adjusted *R*-squared	0.906

SOURCE: RAND analysis of MSHA's Coal Dust Samples dataset.
*** Denotes statistical significance at the 99% confidence level.

[17] Due to the presence of seasonality in the data, we performed a modified Dickey-Fuller *t*-test for a unit root in which the time series has been detrended by a generalized least-squares regression, as proposed by Elliott, Rothenberg, and Stock, 1996. To select the lag order to construct the test, we used the modified Akaike information criterion proposed by Ng and Perron, 2001.

From January 2010 through January 2016, the weighted average dust concentration measurement for workers in these high-risk occupations was 0.549 mg/m^3. Therefore, the estimated impact of the adoption of the CPDM is a 5.4 percent reduction in the average dust concentration.[18] The estimated impact of the reduction in the PEL is an additional 7.6 percent reduction.[19] Therefore, the estimated combined effect is a 13.0 percent reduction in the average dust concentration. The actual impact of the CPDM technology by itself is likely somewhere in between these estimates. Specifically, some of the decline in the lower PEL period may represent continued progress in reducing exposure to respirable coal mine dust due to the adoption of CPDMs. The short time window during which the CPDM was required for compliance sampling prior to the reduction in the PEL makes it challenging to precisely measure this effect in isolation.[20]

To further capture distributional effects, we estimate an additional benefit of CPDMs is that fewer miners will remain working in high-recurrence WLs (i.e., areas with a high number of exceedances).[21] This effect is attributable to the CPDM providing both continuous real-time measurement that allows miners to move further away from the source and end-of-shift measurements that allow miners to take corrective actions to reduce exposures to excessively high-dust concentrations, thus avoiding exceedances and potential violations. Due to data limitations, it is challenging to estimate the impact of CPDMs in high-recurrence WLs. There may be different approaches to estimate this effect in WLs with a high number of exceedances. We choose an approach that is consistent with the methodology in MSHA's QRA (MSHA, 2013). Based on our analysis of dust samples collected before and after the adoption of CPDMs, we estimate that the number of WLs remaining high-recurrence areas based on the pre-2016 definition would be reduced by 81 percent for underground workers and 93 percent for Part 90 miners.[22] This is consistent with data reported in Table 2.5 showing an 86 percent reduction in the number of exceedances for underground workers and a 94 percent reduction in the number of exceedances for Part 90 miners. Therefore, after the adoption of CPDMs we estimate that

[18] We calculate this as –0.0296 ÷ 0.5491 = –0.0538 × 100% = –5.38%.

[19] We calculate this as –0.0417 ÷ 0.5491 = –0.0760 × 100% = –7.60%.

[20] We note that the regression results are generally robust to changes in the specification of the transition time period when CPDMs were first adopted prior to the reduction in the PEL. Including samples from 2016Q1 in the transition period changes the estimated impact from 5.4 to 5.3 percent. Excluding August and September samples from 2016Q3 changes the estimated impact from 5.4 to 4.9 percent.

[21] The estimated average 5.4 percent reduction in exposures is heavily weighted toward miners in low- and mid-recurrence WLs, which account for approximately 95 percent of all WLs.

[22] We calculate this as the average percentage of high-recurrence WLs from 2016 to 2018 compared with the average percentage of high-recurrence WLs from 2010 to 2015. For underground miners, this was 1.0 percent of all WLs between 2016 and 2018 compared with 5.2 percent prior to 2016.

average exposures in previously high-recurrence WLs will be equivalent to average exposures in mid-recurrence WLs.[23]

Step 4: Estimate the Number of Avoided Injuries, Illnesses, and Fatalities

We use three dose-response studies in the health literature to estimate the excess risk of CWP, COPD, or death due to NMRD linked with exposure to respirable coal mine dust. The exposure models estimate risk as an increasing function of age, so the portion of risk attributable to accumulated exposure to respirable coal mine dust can be estimated as the difference in risk with and without occupational exposure. The attributable risk can be expressed in terms of excess cases of disease per 1,000 miners. Based on these models, we estimate impacts for five major adverse health conditions:

1. CWP category 1 (CWP 1+): Based on the International Labour Organization (ILO) International Classification of Radiographs of Pneumoconioses, CWP 1+ includes all cases of simple CWP (ILO categories 1, 2, and 3). CWP 1+ may not be detectable by a chest X-ray. Although miners with CWP 1+ may not exhibit symptoms, some will incur illness and lost workdays attributable to CWP.
2. CWP category 2 (CWP 2+): Consists of CWP1+ excluding the ILO category 1 cases. Miners with CWP2+ may experience chronic cough, excess phlegm, wheezing and shortness of breath, symptoms similar to chronic bronchitis, and have chest X-rays showing lung abnormalities.
3. PMF: Includes all cases of complicated CWP characterized by large opacities (ILO categories A, B, or C). Miners with PMF are at risk of impaired lung function, disability, and premature death. Under the U.S. Department of Labor criteria, miners progressing to the PMF stage qualify as totally disabled due to CWP. PMF is noncurable.
4. COPD: COPD, including emphysema, is characterized by a significant loss of respiratory function. For this study, we only include severe emphysema corresponding to a forced expiratory volume (FEV1) of less than 65 percent of the predicted normal value.
5. NMRD fatality: This includes any premature death associated with emphysema, chronic bronchitis, CWP, or PMF.

To estimate the number of avoided illnesses and fatalities, we rely on dose-response models developed by NIOSH's Respiratory Health Division and used in MSHA's QRA (MSHA, 2013).

[23] We make this assumption because we cannot observe changes in actual exposures by occupation for most high-recurrence WLs in MSHA's Coal Dust Samples dataset due to three limitations: (1) a number of mines in the baseline data temporarily idled or ceased production after 2015, (2) some mines and WLs only started production after 2016, and (3) in many cases production within a mine shifted between WLs over time. Based on a limited sample, certain occupations in high-recurrence WLs experienced average reductions in the range of 0 to 30 percent. It is uncertain whether conditions in these WLs were representative of all high-recurrence WLs in active mines. In addition, the vast majority of WLs would no longer be considered high-recurrence areas after 2016 due to the sharp decline in exceedances.

The models estimate the number of excess cases that will result from a 45-year job tenure with exposure to average levels of respirable coal mine dust by age 73, as follows:

1. Attfield and Seixas (1995) estimate the risk of developing CWP 1+, CWP 2+, and PMF.
2. Kuempel, Vallyathan, and Green (2009) estimate the risk of developing COPD/severe emphysema (FEV1 < 65 percent).
3. Attfield and Kuempel (2008) estimate the risk of premature death due to NMRD.

First, we estimate the number of excess cases of morbidity and mortality due to respiratory disease over a 45-year job tenure, from age 20 to 65, under baseline mining conditions compared with the probability of death without occupational exposure. Occupational exposure is assumed to cease at age 65, but the dose-response models show significantly higher risk by age 73, which may reflect the latency of respiratory disease associated with the accumulation of coal dust particles in the lungs. For example, Miller, MacCalman, and Hutchison (2007) find evidence of a significant 15-year lagged exposure effect in CWP mortality. The Attfield and Kuempel (2008) model finds a significantly greater excess risk of mortality by age 85 compared with age 73 based on the same occupational exposures.[24] We report both estimates. Then, we estimate the number of excess cases of morbidity and mortality due to exposure to respirable coal mine dust after the adoption of CPDMs. We compare the baseline and the postintervention measures to estimate the reduction in fatal and nonfatal respiratory disease.

The Attfield and Seixas (1995) models attribute a greater exposure-specific risk for high-rank bituminous coal mines than low-/medium-rank coal mines. The Attfield and Kuempel (2008) model also includes a third category representing the increased exposure risk for anthracite mines. As a sensitivity analysis for the mortality risk models, we report estimates of the excess risk of death due to NMRD by age 73 and 85. The estimated excess risk of death by age 85 is about two times the estimated excess risk of death by age 73.

The Appendix reports estimates of the excess risk of CWP, COPD, and death due to NMRD for each group of workers (described in Step 2) associated with the baseline exposure levels and reduced exposure levels after the adoption of CPDMs (described in Step 3). The estimates associated with reduced exposure levels can be subtracted from the baseline levels to calculate the impact of CPDMs on the excess risk of respiratory disease due to coal mine dust. To quantify the impact of CPDMs on average exposures, we use an estimate based on the coefficient estimates described in Step 3. We estimate that the impact of CPDMs is at least equivalent to a 5.4 percent reduction, but no larger than a 13.0 percent reduction, in the average dust concentration measurement. The higher value is associated with the combined effect of the

[24] Participants in the original studies were working-age coal miners with only a minority close to retirement age, so the findings may not be generalizable to retired coal miners. The epidemiologic findings were extrapolated to miners past the age of retirement.

introduction of CPDMs and the reduction in the PEL mandated by the MSHA coal mine dust rule. We adopt a conservative approach using only the first coefficient estimate, which is equivalent to a 5.4 percent reduction in exposure to respirable coal mine dust. We also present a sensitivity analysis showing the effect of using a relatively higher estimate of a 9.2 percent reduction, which is between the 5.4 and 13.0 percent estimates described above.

Table 2.7 reports the potential number of cases of fatal and nonfatal disease avoided due to the adoption of CPDMs. The decrease in the number of cases is attributable to the reduction in average respirable coal mine dust exposure, including a reduction in the number of workers in high-recurrence WLs due to the decline in exceedances; we assume that going forward these workers would experience conditions more similar to mid-recurrence WLs.[25]

Table 2.7. Estimated Number of Fatal and Nonfatal Illnesses Avoided Due to Reduction in Respirable Coal Mine Dust Exposure over 45 Years

Disease	Total Number of Cases Avoided	Average Annual Number of Cases Avoided
CWP 1+	218	4.8
CWP 2+	182	4.0
PMF	128	2.9
COPD	87	1.9
Total nonfatal illnesses	615	13.7
Deaths due to NMRD		
By age 73	10	0.2
By age 85	23	0.5

NOTE: Totals may not sum precisely due to rounding.

Step 5: Monetize Avoided Injuries, Illnesses, and Fatalities

We used two approaches to estimate the economic benefits of NIOSH's contribution to the adoption of CPDMs. First, we use estimates of medical costs and productivity losses to monetize benefits associated with avoided cases of fatal and nonfatal respiratory disease. Separately, we use willingness-to-pay (WTP) estimates from the available economic literature to monetize these impacts.

We first made assumptions about the timing and value of future benefits. Our analysis estimates a stream of benefits over a 65-year time horizon to capture the full impact of reduced

[25] The results are moderately sensitive to this second assumption. For example, changing the estimated reduction in exposures for miners in high-recurrence WLs from our estimate of approximately 30 to 20 percent would reduce the overall number of cases avoided by slightly more than 10 percent.

exposure levels on future cases of respiratory disease. This accounts for an average job tenure of 45 years and an average lag of 20 years to account for the latency of respiratory diseases in this study. Benefits will phase in over several decades because the risk of disease depends on cumulative exposures to respirable coal mine dust. Furthermore, we estimate a delay in the timing of benefits because a coal miner joining the workforce today would benefit from the adoption of CPDMs for their entire career, while current workers would benefit from reduced exposure levels for a shorter duration over the remainder of their career.

We use an S-curve to approximate the expected timing of the monetized benefits. Specifically, we estimate a cumulative Poisson distribution with a mean of 20 years to account for the latency of disease and new workers entering the workforce.[26] The benefits of using a single probability distribution are twofold: it avoids the need to make additional assumptions about workforce replacement and disease latency and progression, and estimates a smooth, continuous stream of benefits over time. Using this probability distribution, the steady state equilibrium associated with the reduction in exposures is nearly achieved in about 32 years.[27] We also present a sensitivity analysis illustrating a more gradual transition to the new steady state. In both cases, we include an additional one-year lag to allow time for miners to experience an entire year at reduced exposure levels before attributing benefits to CPDM use. We estimate the value of future benefits will increase by 2 percent annually. We therefore adjust WTP estimates to address real income growth and adjust medical cost estimates to address increases in real medical costs. To reflect societal preference for the timing of benefits, we apply discount rates of 3 and 7 percent to the future stream of monetized benefits. Finally, we calculate the present value of these benefits over 65 years on an annualized basis using the two discount rates.

The present value (PV) is calculated as:

$$\text{PV} = \sum_{t_1}^{T} \frac{B_t}{(1-i+r)^{t-t_1}} \qquad \textit{(Equation 2)}$$

where B_t is the value of benefits accrued in year t, T is the number of years in the forecast period, i is the growth rate in real income relative to monetized future benefits, and r is the discount rate.

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[26] The motivation for this approach is described in detail in MSHA, 2014a, pp. 195–201. In its regulatory analysis, MSHA chose a single probability distribution to phase in benefits over time to give a reasonable approximation for the complex relationships among worker exposure, worker replacement, and the progression of respiratory disease. Similar approaches have been used by federal agencies in other risk assessments and regulatory analyses; see Environmental Protection Agency (EPA), 2011a, 2011b; Food Safety and Inspection Service, 2012.

[27] After ten years less than 1 percent of the benefits in the steady state will be achieved, after 20 years approximately half of the steady state benefits will be achieved, and after 30 years approximately 98 percent of the steady state benefits will be achieved.

The annualized value (AV) is then calculated as:[28]

$$\text{AV} = \text{PV}\left[\frac{r\times(1+r)^{(T-1)}}{(1+r)^{T}-1}\right] \qquad \textit{(Equation 3)}$$

To calculate the medical costs of CWP, COPD, and death due to NMRD, we use health cost data from several sources. For CWP, we use the most recent annual medical cost data from the Black Lung Disability Trust Fund as reported by GAO for FY 2017. We multiply the average annual medical cost of approximately $7,100 (in 2018 dollars) by 20 years to estimate the lifetime medical costs of CWP. This is based on an average life expectancy of approximately 76 years for males (Arias, Xu, and Kochanek, 2019). Many miners wait until near retirement age (around their late 50s) before seeking diagnosis or treatment for CWP or starting the process of qualifying for federal black lung benefits.[29] Therefore, we use 20 as an approximation for years of medical treatment attributable to CWP. We do not have more detailed estimates of the cost breakdown for more severe cases, so we use one figure for all cases of CWP. This may potentially overestimate the costs of less severe cases of CWP and underestimate the costs of more severe cases of CWP, including PMF.

For COPD, we use an average annual medical cost estimate of approximately $15,300 (in 2018 dollars) from Hilleman et al. (2000). We again use 20 as an approximation for years of medical treatment attributable to COPD. For deaths due to NMRD, we use a weighted average based on the number of male occupational deaths attributable to each disease for lifetime expected medical costs (approximately $290,000) plus the expected medical costs per death from Leigh (2011) (approximately $200,000). NIOSH's finding that the YPLL for deaths due to CWP has increased to 12.6 (Mazurek et al., 2018) due to the increasing severity and rapid progression of CWP among coal miners suggests that this estimate may overstate lifetime medical costs because miners affected by severe cases of CWP may be dying more rapidly than in the past.

To account for lost earnings, fringe benefits, and work done outside of the labor force (i.e., home production), we also estimated productivity losses. We derived estimates of productivity losses based on the present value of future lifetime production for the affected workforce.[30] The average present value of lost production due to a fatality is based on a weighted average for men and women younger than and older than 65, respectively, according to the distribution of occupational fatalities for these groups and reflecting the average salary for coal miners in the United States. We followed the approach in Leigh (2011), in multiplying estimates

[28] The annualized value represents an equivalent annual monetized benefit which, if accrued at a constant rate over 65 years, would equal the total present value calculated in Equation 2.

[29] Personal communication with NIOSH's Respiratory Health Division on June 20, 2019.

[30] Using estimates in Grosse, Krueger, and Mvundura, 2009, we applied a 3-percent discount rate to all future production.

of lost production by the morbidity-to-mortality ratios in Rice, Hodgson, and Kopstein (1985), to estimate the benefits of avoided morbidity.[31] We adjusted all estimates to 2018 dollars using the gross domestic product implicit price deflator.

For CWP 1+, we assume some coal miners will not be diagnosed or treated, and many will not miss more than a few days of work due to illness. Therefore, we do not include productivity losses for cases of CWP 1+. CWP 2+ is not considered to be disabling, but likely will result in a significant health impediment for coal miners. PMF and severe emphysema can both result in totally disability and inability to work. For cases of CWP 2+, PMF, and COPD, we use estimates of productivity losses based on Leigh (2011). This results in productivity losses of approximately $540,000 for nonfatal cases of CWP and $580,000 for nonfatal cases of COPD. Adding productivity losses for fatal cases to these estimates using the same approach yields estimates of approximately $940,000 for deaths due to NMRD.

Table 2.8 reports the estimated medical costs and productivity losses for cases of fatal and nonfatal respiratory disease in this study.

Table 2.8. Estimated Medical Costs and Productivity Losses Attributable to Individual Cases of Fatal and Nonfatal Respiratory Disease

Disease	Medical Costs ($2018)	Productivity Losses ($2018)	Total ($2018)
CWP 1+	$140,000	$0	$140,000
CWP 2+	$140,000	$540,000	$680,000
PMF	$140,000	$540,000	$680,000
COPD	$310,000	$590,000	$890,000
Death due to NMRD	$490,000	$940,000	$1,430,000

NOTE: Estimates are rounded to the nearest $10,000.

Table 2.9 reports estimates of the avoided medical costs and productivity losses associated with cases of fatal and nonfatal respiratory disease due to the adoption of CPDMs.

[31] These estimates do not include the costs associated with overtime and labor replacement costs, such as the cost of training new hires.

Table 2.9. Estimated Avoided Medical Costs and Productivity Losses for Cases of Fatal and Nonfatal Respiratory Disease Due to Reduction in Exposure to Coal Mine Dust After the Adoption of Personal Dust Monitors (over 65 Years)

Disease	Total Number of Cases Prevented	Annualized Monetized Benefits ($2018 millions, 3% discount rate)	Annualized Monetized Benefits ($2018 millions, 7% discount rate)
CWP 1+	218	$0.7	$0.3
CWP 2+	182	$2.8	$1.3
PMF	128	$2.0	$0.9
COPD	87	$1.8	$0.8
Subtotal: Nonfatal disease	615	$7.3	$3.4
Death due to NMRD (by age 73)	10	$0.3	$0.1
Death due to NMRD (by age 85)	23	$0.8	$0.4
Total (including deaths by age 73)	–	$7.6	$3.6
Total (including deaths by age 85)	–	$8.0	$3.8

NOTE: Totals may not sum precisely due to rounding.

Separately, we use WTP estimates to monetize the cost burden of respiratory disease. This approach is consistent with MSHA's regulatory analysis of the coal mine dust rule and is recommended by the U.S. Office of Management and Budget to assess the impact of federal regulations. To monetize benefits associated with avoided deaths due to NMRD, we used a VSL estimate of $10.0 million measured in 2018 dollars (Viscusi and Aldy, 2003).[32] Regulatory analyses generally use VSL estimates to represent the monetary value of society's WTP for an incremental reduction in the probability of a fatality. From the same study, we use a relatively lower estimate of approximately $71,000 for cases of CWP 1+ based on the value of lost workday injury. For cases of CWP 2+, we use an estimate of approximately $490,000 (in 2018 dollars) from the EPA's Office of Air and Radiation for avoided cases of chronic bronchitis (EPA, 2011b). For cases of PMF and COPD, we rely on estimates from MSHA's final regulatory analysis for the coal mine dust rule. These estimates are derived from Viscusi, Magat, and Huber (1991), which measures WTP for reducing the risk of chronic bronchitis, and Magat, Viscusi, and Huber (1996), which measures WTP for reducing the risk of nerve disease. The median WTP values were 32 percent and 40 percent of the WTP to avoid a fatal injury, respectively. We use the average of these estimates, 36 percent of the VSL estimate or approximately $3.6 million. Table 2.10 reports the WTP estimates for fatal and nonfatal respiratory disease in this study.

[32] The U.S. Department of Transportation (DOT) recommends using a VSL of $9.6 million (in 2015 dollars) for regulatory analyses. DOT's guidance document, Moran and Monje, 2016, describes the motivation and methodology for using WTP estimates to value avoided fatal and nonfatal injuries and illnesses.

Table 2.10. Monetized Willingness-to-Pay Estimates for Fatal and Nonfatal Respiratory Disease

Disease	WTP Estimate ($2018 millions)
CWP 1+	$0.07
CWP 2+	$0.49
PMF	$3.60
COPD	$3.60
Death due to NMRD	$10.0

Table 2.11 reports the monetized benefits associated with the adoption of CPDMs using the WTP measures described above.

Table 2.11. Estimated Willingness-to-Pay Estimates for Risk Reduction in Fatal and Nonfatal Respiratory Disease Due to Reduction in Exposure to Coal Mine Dust After the Adoption of Personal Dust Monitors (over 65 Years)

Disease	Total Number of Cases Prevented	Annualized Monetized Benefits ($2018 millions, 3% discount rate)	Annualized Monetized Benefits ($2018 millions, 7% discount rate)
CWP 1+	218	$0.3	$0.2
CWP 2+	182	$2.0	$0.9
PMF	128	$10.5	$4.9
COPD	87	$7.1	$3.3
Subtotal: Nonfatal disease	615	$20.0	$9.4
Death due to NMRD (by age 73)	10	$2.2	$1.0
Death due to NMRD (by age 85)	23	$5.3	$2.5
Total (including deaths by age 73)	–	$22.2	$10.4
Total (including deaths by age 85)	–	$25.3	$11.8

NOTE: Totals may not sum precisely due to rounding.

The monetized benefits of MSHA's coal mine dust rule reflect the impact of three of the final rule's provisions: lowering the respirable coal mine dust standard, use of a MSHA inspector's single sample to determine compliance, and redefining the term "normal production shift." MSHA estimates the annualized economic benefits of these three provisions are $42.4 million using a 3-percent discount rate or $23.0 million using a 7-percent discount rate (in 2018 dollars) (MSHA, 2014a). MSHA's economic analysis does not estimate the impact of the adoption of CPDMs, which is the focus of this report. Therefore, it is not feasible to attribute a specific percentage of the monetized benefits of MSHA's coal mine dust rule to NIOSH. Furthermore, it is challenging to separate the impacts of requiring the use of CPDMs and mandating a reduction in the PEL as both provisions of the rule are intended to reduce exposure to excessively high concentrations of respirable coal mine dust. For example, both requirements are likely to reduce the number of workers in WLs with a large number of excessively high dust concentration measurements. Our initial estimate of the impact of CPDMs is based on inspector samples collected during the six-month period when CPDMs were being used prior to the mandatory reduction in the PEL. However, we believe the effect would be larger if measured over a longer time horizon because there would be more time for miners to take corrective actions to reduce exposures. We estimate that the actual value is somewhere between the reduction in average dust concentration measurements during the first six months of CPDM use and the relatively larger reduction seen between 2016 and 2018, which reflects the combined effect of both requirements. Therefore, our estimates of the economic benefits of dust monitors may overlap with the benefits monetized in MSHA's analysis.[33] With the development of CPDMs, NIOSH's contributions support several provisions of the MSHA rule, such as providing a mechanism to facilitate compliance with the reduction in the PEL. The MSHA rule mandates a multipronged approach to reduce exposure to respirable coal mine dust, and the CPDM requirement is a supporting pillar. As we show in this report, CPDMs have contributed to more reliable operator samples and a reduction in the number of samples exceeding the PEL (currently less than 1 percent), reducing exposure to respirable coal mine dust and reducing the rate of noncompliance.

Sensitivity Analyses

As we describe in Step 3, we estimate that the first months after the initial adoption of CPDMs saw a 5.4-percent reduction in exposures to respirable coal mine dust. We estimate that the subsequent reduction in the PEL mandated by MSHA resulted in an additional 7.6-percent reduction, contributing to a combined 13.0-percent reduction by the end of 2018. The actual impact of CPDMs is likely somewhere in between these values; however, the short time period before the transition to the new regulatory regime makes it challenging to precisely measure the impact in isolation. The downward quarterly trend in average dust concentration measurements after 2016, shown in Figure 2.3, also suggests that mine operators continued to take corrective actions based in part on CPDM measurements to reduce exposures. As a sensitivity analysis, we present the impact of a relatively higher 9.2-percent reduction in exposures, which is between the 5.4- and 13.0-percent reduction estimates described above. Based on the exposure risk models described in this chapter, this larger estimated reduction results in approximately a 40-percent increase in the number of cases of fatal and nonfatal respiratory disease prevented and a corresponding 40- to 45-percent increase in monetized benefits. Table 2.12 reports the results of

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[33] For example, one area of overlap is that we anticipate the use of CPDMs will reduce the number of workers in high-recurrence work locations and MSHA estimates mandating a reduction in the PEL will have the same effect.

this sensitivity analysis for estimating the monetized benefits associated with the adoption of CPDMs using both avoided medical costs and productivity losses and WTP estimates.

Table 2.12. Estimated Benefits Including Avoided Cases of Fatal and Nonfatal Respiratory Disease Due to Reduction in Exposure to Coal Mine Dust After the Adoption of Personal Dust Monitors (over 65 Years) with a Larger Reduction in Exposures

		Medical Cost and Productivity Loss Estimates		Willingness-to-Pay Estimates	
Disease	Total Number of Cases Prevented	Annualized Monetized Benefits ($2018 millions, 3% discount rate)	Annualized Monetized Benefits ($2018 millions, 7% discount rate)	Annualized Monetized Benefits ($2018 millions, 3% discount rate)	Annualized Monetized Benefits ($2018 millions, 7% discount rate)
CWP 1+	318	$1.0	$0.5	$0.5	$0.2
CWP 2+	258	$4.0	$1.9	$2.9	$1.3
PMF	178	$2.8	$1.3	$14.6	$6.8
COPD	128	$2.6	$1.2	$10.5	$4.9
Subtotal: Nonfatal disease	883	$10.4	$4.9	$28.4	$13.3
Death due to NMRD (by age 73)	15	$0.5	$0.2	$3.3	$1.5
Death due to NMRD (by age 85)	35	$1.1	$0.5	$7.9	$3.7
Total (including deaths by age 73)	–	$10.9	$5.1	$31.7	$14.8
Total (including deaths by age 85)	–	$11.5	$5.4	$36.3	$17.0

NOTE: Totals may not sum precisely due to rounding.

As we describe in Step 5, the estimated monetized benefits are sensitive to assumptions regarding the timing of future benefits, including the time horizon and probability function used to estimate the transition to the new steady state equilibrium. As a second sensitivity analysis, we present the relative impact of estimating a more gradual phase-in period. Using the Poisson distribution function, we use a mean of 30 instead of 20 years to model the timing of future benefits. Using this probability distribution, the steady state equilibrium associated with the reduction in exposures is nearly achieved in about 44 years.[34] Table 2.13 reports the results of our sensitivity analysis for a relatively slower transition path to reaching the new steady state equilibrium using both avoided medical costs and productivity losses and WTP estimates. Changing this assumption would reduce the total number of fatal and nonfatal cases prevented by approximately 20 percent during the first 65 years after the adoption of CPDMs and reduce the

[34] After 30 years approximately half of the steady state benefits will be achieved and after 40 years approximately 95 percent of the steady state benefits will be achieved.

monetized benefits by approximately 25 to 45 percent. This range is relatively large because it represents the estimated monetized benefits using discount rates of both 3 and 7 percent.

Table 2.13. Estimated Benefits Including Avoided Cases of Fatal and Nonfatal Respiratory Disease Due to Reduction in Exposure to Coal Mine Dust After the Adoption of Personal Dust Monitors (over 65 Years) with a More Gradual Phase-in Period

		Medical Cost and Productivity Loss Estimates		Willingness-to-Pay Estimates	
Disease	**Total Number of Cases Prevented**	**Annualized Monetized Benefits ($2018 millions, 3% discount rate)**	**Annualized Monetized Benefits ($2018 millions, 7% discount rate)**	**Annualized Monetized Benefits ($2018 millions, 3% discount rate)**	**Annualized Monetized Benefits ($2018 millions, 7% discount rate)**
CWP 1+	169	$0.5	$0.2	$0.3	$0.1
CWP 2+	142	$2.1	$0.8	$1.5	$0.5
PMF	100	$1.5	$0.5	$7.8	$2.8
COPD	68	$1.3	$0.5	$5.3	$1.9
Subtotal: Nonfatal disease	478	$5.4	$2.0	$14.8	$5.4
Death due to NMRD (by age 73)	8	$0.2	$0.1	$1.6	$0.6
Death due to NMRD (by age 85)	18	$0.6	$0.2	$3.9	$1.4
Total (including deaths by age 73)	–	$5.6	$2.0	$16.4	$6.0
Total (including deaths by age 85)	–	$5.9	$5.4	$18.7	$6.8

NOTE: Totals may not sum precisely due to rounding.

NIOSH's Continued Role in Improving the Personal Dust Monitor

NIOSH continues to work with industry and labor to improve the technology and use of CPDMs. Since the Upper Big Branch Mine disaster,[35] NIOSH has continued to evaluate the use of CPDMs and has issued several RFPs for improving dust monitors. NIOSH funded one additional project in 2017 and three additional projects in 2018—including early investments in developing different continuous sampling technologies and real-time monitoring of silica exposure.[36]

NIOSH researchers have investigated various improvements to the current version of the CPDM. Potential improvements include ergonomic redesign, weight reduction, and additional metrics to validate that the monitor is being used properly (e.g., a built-in accelerometer to make

[35] On April 5, 2010, 29 miners were killed at the Upper Big Branch Mine in Montcoal, West Virginia, when high concentrations of float coal mine dust allowed to accumulate in violation of health and safety standards contributed to a methane-gas ignition causing a massive coal dust explosion.

[36] Personal communication with NIOSH's Office of Mine Safety and Health Research on January 30, 2019.

sure the miner is walking around and does not leave the device hanging in a different location). Industry has also cited concerns that the CPDM generates electromagnetic interference with the proximity detection system used with continuous miners. Miners using CPDMs in the vicinity of continuous miners may be at risk of physical harm (i.e., being crushed) if they deactivate or disable their proximity reader to ensure they get valid dust samples using the CPDM. Current regulations require both detectors and CPDMs be worn. NIOSH is also conducting research on techniques that can be used to mitigate the electromagnetic interference from the CPDM.

Finally, NIOSH stakeholders have sought a real-time silica dust monitor for coal mining. Silica dust can be more toxic than coal mine dust and can cause more rapid progression of respiratory disease. In December 2018, a National Public Radio (NPR)/*Frontline* report found thousands of instances where miners were exposed not only to coal dust but also hazardous levels of silica dust (Berkes, Jingnan, and Benincasa, 2018). Over the last 30 years, NPR/*Frontline* found approximately 15 percent of coal mine samples showed excessive silica levels that violated federal health standards. NIOSH researchers say the technology for a real-time silica dust monitor does not currently exist but is being studied. Gravimetric samplers are still used for silica dust sampling, but this requires samples to be sent to MSHA laboratories for testing, meaning the results can take weeks to obtain.[37] To date, MSHA has not proposed additional regulation of silica in coal mines or a more stringent PEL for silica dust. However, on August 29, 2019, MSHA issued a request for information soliciting information and data on best practices to protect miners' health from exposure to quartz in respirable dust, including an examination of an appropriately reduced permissible exposure limit, potential new or developing protective technologies, and/or technical and educational assistance (MSHA, 2019b).

Conclusion

NIOSH's efforts in awarding research grants, collaborating with industry and labor in testing and developing prototypes, disseminating research findings, and conducting outreach to miners played a major role in the development and adoption CPDMs for coal miners. The advent of the technology has supported federal requirements mandating lower permissible exposure limits and more frequent compliance sampling, providing a mechanism to reduce noncompliance and realize additional benefits. Specifically, having access to continuous real-time and end-of-shift measurement allows coal miners to take corrective actions to reduce exposure to excessively high levels of respirable coal mine dust. One of the contributions of the CPDM has been to improve the reliability of operator samples, which provides important information to miners on exposure levels and can help mine operators develop better ventilation plans. Without NIOSH's

[37] Under MSHA's coal mine dust rule, all samples for silica analysis are collected by MSHA inspectors.

contribution, the attained reductions in exposure to respirable coal mine dust may not have been as successful and improvements in work practices based on corrective actions linked to CPDMs would have been less likely to occur. It is unlikely similar technology would have been developed without NIOSH. The technology has now been available for more than a decade and no other countries, or other manufacturers within the United States, have developed similar devices.

We estimate that underground miners and Part 90 Miners will continue to benefit from reduced exposure to excessive levels of respirable coal mine dust due to the adoption of CPDMs. We estimate the economic benefits associated with risk reductions in fatal and nonfatal respiratory disease will be \$22.2 million to \$25.3 million using a 3-percent discount rate or \$10.4 to \$11.8 million using a 7-percent discount rate on an annualized basis using the willingness-to-pay estimates discussed in this chapter. We separately estimate that the economic benefits will be \$7.6 million to \$8.0 million using a 3-percent discount rate or \$3.6 million to \$3.8 million using a 7-percent discount rate on an annualized basis in terms of avoided medical costs and productivity losses.

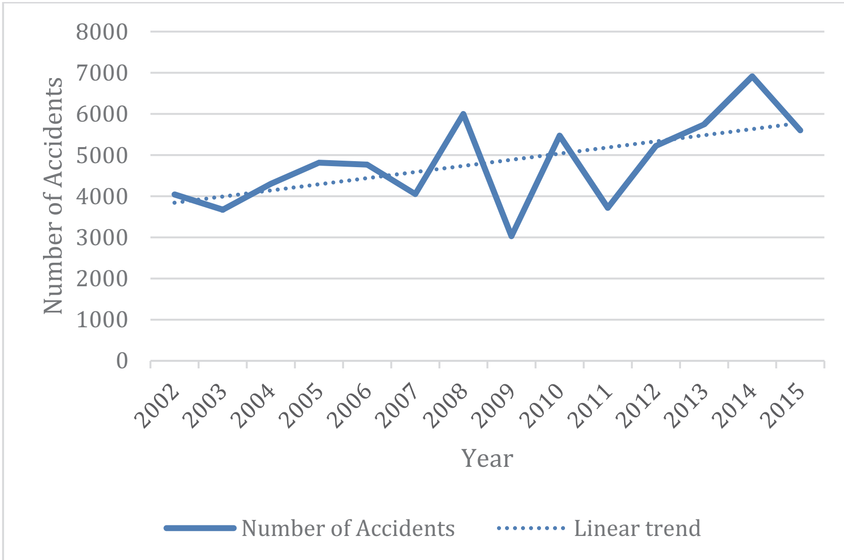
3. Improved Ambulance Design

Ambulances—vehicles used to transport sick or injured individuals—have been in use for centuries. The design of ambulances has evolved along with advances in technology and changes in requirements. Modern ambulance designs began to take shape in the 1970s, when the DOT requested that the General Services Administration (GSA) introduce the first purchase specification for an ambulance. These purchase specifications—first released in 1974 and with major revisions now released every 5–7 years—described how an ambulance should be constructed (NIOSH, 2017a). Today there are three main sources of guidance for how ground ambulances should be designed to balance function and safety: GSA purchase specifications (GSA, 2019), the National Fire Protection Association's Standard for Automotive Ambulances (NFPA, 2019), and the Commission on Accreditation of Ambulance Services' Ground Vehicle Standard for Ambulances (see CAAS GVS, 2019). Research conducted by organizations such as NIOSH provides evidence on which to base these standards.

These safety standards are important because being transported via ambulance can be hazardous. According to data from the National Automotive Sampling System–General Estimates System (NASS-GES), there were an average of over 4,800 crashes each year involving ambulances—a statistic that has been slowly increasing over time, as shown in Figure 3.1. From 2002 to 2015, there were an average of nine fatalities and 1,200 injuries due to crashes among ambulance occupants each year.[38] This figure does not include injuries that result from hard-braking events or other crash-avoidance maneuvers.

[38] These values do not include others involved in these crashes—occupants of other vehicles and those who are not occupants of a vehicle—although, as shown in Figure 3.2, those individuals make up the majority of injuries. This report focuses on ambulance occupants.

Figure 3.1. The Number of Ambulance Crashes Is Slowly Increasing over Time



SOURCE: RAND analysis of NASS-GES data.

Analysis of NASS-GES and the Fatality Analysis Reporting System (FARS) by NHTSA, shown in Figure 3.2, has shown that ambulance passengers—occupants other than the driver—make up 29 percent of those injured and 21 percent of those killed in these crashes.[39] Ambulance passengers include anyone riding in an ambulance, such as EMS workers, patients, and those accompanying patients. These passengers may be seated in the front of the vehicle next to the driver, or may be located in the patient compartment of the ambulance. Until recent design changes were implemented, the ambulance patient compartment was a particularly risky environment; it could contain loose or unrestrained equipment that could strike passengers in the event of a crash or hard-braking event. Even the patient cot, a device not previously required to be designed or tested for crash loads, has been known to separate from the floor of the patient compartment and injure occupants. Further, the layout of the interior previously included cabinets and equipment that passengers could strike in the event of a crash or hard-braking event.

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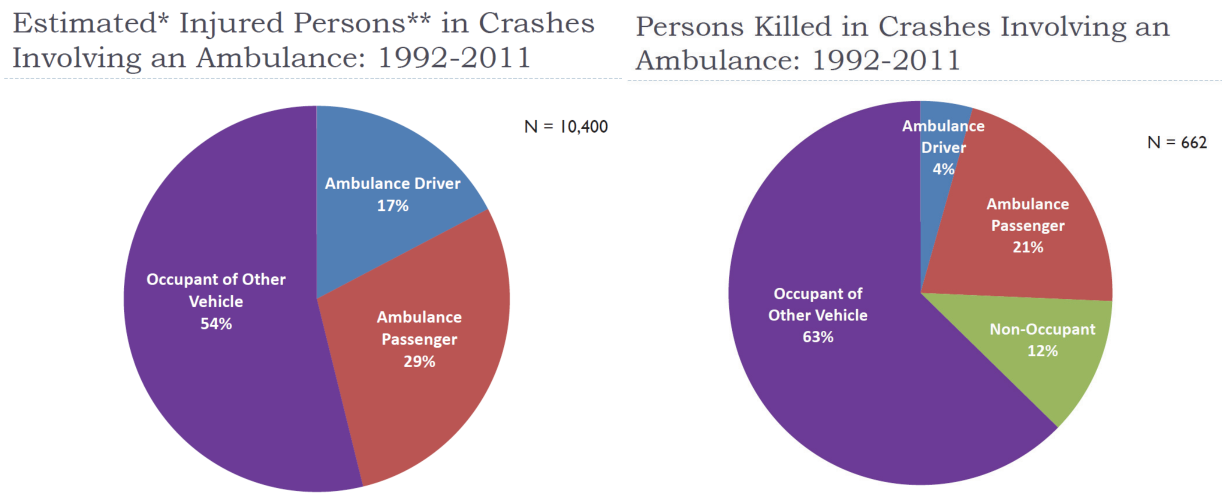
[39] NASS-GES comes from a nationally representative sample of police reports on all types of crashes. Weights are provided to estimate the national statistics. Some of the large amounts of year-by-year variation, such as in Figures 3.1 and 3.5, is likely due to the small sample size of crashes involving ambulances; we present national estimates based on NASS-GES weights. Because NASS-GES it is a random sample and not a national census, it can miss recording relatively rare types of crash outcomes. This is the case for crash fatalities among ambulance occupants. For example, NASS-GES observed no fatalities among ambulance occupants during crashes in 2015. The FARS data provide a complete census of all crashes involving fatalities. We can use the FARS data to find that there were 11 traffic fatalities among ambulance occupants in 2015; 1 was a driver, 3 were front-seat passengers, 6 were in the patient compartment, and 1 had an unknown location.

Figure 3.2. Ambulance Passengers Make Up 29 Percent of Injuries and 21 Percent of Fatalities in Crashes Involving Ambulances



SOURCE: NHTSA, 2014, pp. 17–18.
* Data represent mean number of crashes and injuries over 5 years.
** Does not include data on nonoccupants of a vehicle (pedestrians and pedal cyclists) in injured persons. RAND analysis of NASS-GES data from 2002 to 2015 finds that 3.5% of injuries are to nonoccupants.

In addition, EMS workers have reported that it is difficult to perform their jobs while wearing standard safety restraints (Larmon, LeGassick, and Schriger, 1993). This has led many to work unrestrained in the patient compartment. In serious crashes investigated by NHTSA, 84 percent of EMS providers in the patient compartment were not restrained at the time of the crash (Smith, 2015). While 96 percent of patients were restrained at the time of the crash, only 33 percent of patients were restrained properly with both lateral belts and shoulder straps (Smith, 2015). Unrestrained individuals are significantly more likely to be injured or killed in a crash, and may also injure those around them (Levick, Li, and Yannaccone, 2001a, 2001b) because unrestrained individuals can become projectiles themselves. Similar issues may apply to improperly restrained individuals. Previous restraints and seats were not designed for the unique requirements in an ambulance patient compartment. Passengers in the patient compartment may not be facing forward, and may need to move around to reach various locations in the compartment.

Overview of NIOSH's Activities in Ambulance Design

In the early 2000s, NIOSH recognized ambulance transportation as a dangerous workplace that could potentially be made safer through research. Early research efforts involved applications for internal funding, but quickly grew through collaboration with a wide array of partners, from both the government and private sector, who shared a common vision that systematic research could lead to safety improvements for ambulance passengers. NIOSH's work and partnerships in support of ambulance safety has directly led to a wide variety of outputs, including not only data collection, publications, and presentations, but also new production standards and changes in manufacturers' designs. Table 3.1 lists the publication date of reports and standards that were led or supported by NIOSH. The subsequent text discusses these and other NIOSH activities in more detail.

Table 3.1. Publication Date of Reports and Standards on Ambulance Design That Were Led or Supported by NIOSH

Year	Publications and Standards
2003	Proudfoot, S., N. Romano, T. Bobick, and P. Moore, "Ambulance Crash-Related Injuries Among Emergency Medical Services Workers–United States, 1991-2002," *Morbidity and Mortality Weekly Report*, Vol. 52, No. 8, 2003, pp. 154–156.
2005	Proudfoot, Steven L., "Ambulance Crashes: Fatality Factors for EMS Workers," *Emergency Medical Services*, Vol. 34, No. 6, 2005, 71–73.
	Green, J. D., R. S. Current, T. G. Bobick, S. Proudfoot, N. T. Romano, and P. H. Moore, "Reducing Vehicle Crash-Related EMS Worker Injuries Through Improvements in Restraint Systems," *Proceedings of the XVIIth World Congress on Safety and Health at Work, September 16–20, 2005, Orlando, Florida*, Itasca, Ill.: National Safety Council, 2005.
2007	Proudfoot, Steven, Paul Moore, and Roger Levine, "Safety in Numbers: A Survey on Ambulance Patient Compartment Safety," *Journal of Emergency Medical Services*, Vol. 32, No. 3, 2007, pp. 86–90.
	Current, R. S., P. H. Moore, J. D. Green, J. R. Yannaccone, G. R. Whitman, and L. A. Sicher, "Crash Testing of Ambulance Chassis Cab Vehicles," Society of Automotive Engineers (SAE) Technical Paper 2007-01-4267, Warrendale, Pa., SAE, 2007.
2008	Green J. D., D. Ammons, P. Moore, R. Whisler, A. Isaacs, and J. White, "Creating a Safe Work Environment for Emergency Medical Service Workers," *Proceedings of the American Society of Safety Engineer's Professional Development Conference, June 9–12, 2008, Las Vegas, Nevada*.
2010	Green, J. D., J. R. Yannaccone, R. S. Current, L. A. Sicher, P. H. Moore, and G. R. Whitman, "Assessing the Performance of Various Restraints on Ambulance Patient Compartment Workers During Crash Events," *International Journal of Crashworthiness*, Vol. 15, No. 5, 2010, pp. 517–541.
	SAE recommended practice document J2917 (5/2010, revised 8/2016): "Occupant Restraint and Equipment Mounting Integrity—Frontal Impact Ambulance Patient Compartment"
2011	SAE recommended practice document J2956 (6/2011, revised 8/2016): "Occupant Restraint and Equipment Mounting Integrity—Side Impact Ambulance Patient Compartment"
	Wilson, D. P., J. Lockett-Reynolds, T. B. Malone, K. M. Duma, L. W. Avery, and J. D. Green, "Human Systems Integration (HIS) Requirements for First Responders in Emergency Response," paper presented at the American Society of Naval Engineers Human Systems Integration Symposium, October 25–27, 2011, Vienna, Va.
2014	SAE recommended practice document J3026 (8/2014, revised 11/2016): "Ambulance Patient Compartment Seating Integrity and Occupant Restraint"
	SAE recommended practice document J3027 (7/2014, revised 11/2016): "Ambulance Litter Integrity, Retention, and Patient Restraint"
	SAE recommended practice document J3043 (7/2014): "Ambulance Equipment Mount Device or Systems"
	SAE recommended practice document J3044 (6/2014, revised 8/2016): "Occupant Restraint and Equipment Mounting Integrity—Rear Impact Ambulance Patient Compartment"
2015	Avery, Larry, Allie Jacobs, Jennifer Moore, Carlotta Boone, Jennifer Marshall, Allison Barnard Feeney, Y. Tina Lee, Deogratias Kibira, and Tom Malone, *Ambulance Patient Compartment Human Factors Design Guidebook*, Washington, D.C.: Department of Homeland Security, 2015.
2016	SAE recommended practice document J3058 (11/2016): "Ambulance Interior Storage Compartment Integrity"

Year	Publications and Standards
2017	SAE recommended practice document J3057 (2/2017): “Ambulance Modular Body Evaluation-Quasi-Static Loading for Type I and Type III Modular Ambulance Bodies”
	SAE recommended practice document J3059 (4/2017): “Ambulance Patient Compartment Seated Occupant Excursion Zone Evaluation”
	SAE recommended practice document J3102 (3/2017): “Ambulance Patient Compartment Structural Integrity Test to Support SAE J3027 Compliant Litter Systems”
	NIOSH, *Improving EMS Worker Safety in the Patient Compartment*, Washington, D.C.: Department of Homeland Security, 2017.
	Reichard, Audrey A., Suzanne M. Marsh, Theresa R. Tonozzi, Srinivas Konda, and Mirinda A. Gormley, “Occupational Injuries and Exposures Among Emergency Medical Services Workers,” *Prehospital Emergency Care*, Vol. 21, No. 4, 2017, pp. 420–431.
	NIOSH developed a seven-module, 70-minute video series covering a significant portion of the work conducted by the federal government over the last 15 years related to ambulance crash safety. See NIOSH, 2017a.

In 2002, NIOSH began its first partnership on this topic, collaborating with the Canadian Forces Health Services Group, the U.S. Army Tank-Automotive and Armaments Command, and the Ministry of Health and Long-Term Care, Ontario, “to evaluate the capability of mobile restraint systems to protect occupants in the patient compartment of an ambulance” (Current et al., 2007, p. 316). This in turn led to a continuous series of partnerships with government agencies, industry representatives, and other stakeholders.

Some of these partnerships have involved NIOSH participation in surveillance efforts. The NIOSH Fatality Assessment and Control Evaluation Program assisted the NHTSA Special Crash Investigation Program in investigating ambulance crashes, in support of NHTSA’s duty to conduct crash investigations. From 2001 to 2012, NHTSA conducted 32 investigations, and NIOSH conducted six investigations (EMS, 2015). In 2004, NHTSA and the National Registry of Emergency Medical Technicians developed and administered an ambulance safety snapshot (Proudfoot, Moore, and Levine, 2007). NIOSH provided technical advice on the questionnaire and data analysis. The partnership between NHTSA and NIOSH also led to a NHTSA-funded study where NIOSH conducted telephone surveys on nonfatal work-related injuries among EMS providers identified in the occupational supplement to the National Electronic Injury Surveillance System (NEISS-Work).[40] This survey captured details on all types of injuries occurring to EMS providers, including but not limited to motor vehicle crashes.

Other partnerships have involved developing detailed testing protocols to physically crash test ambulances. For example, NIOSH worked with independent automotive test facilities (MGA Research Corporation, Transportation Research Center, and the Center for Advanced Product Evaluation) to physically crash test 17 ambulances that had their patient compartments fitted

[40] The NEISS-Work data are collected by the NIOSH Division of Safety Research in partnership with the U.S. Consumer Product Safety Commission (CPSC), the operator of the basic NEISS program. See NIOSH, 2019a.

with accelerometers. These accelerometers measure the acceleration of the patient compartment in an industry-standard 30 mph crash test setting. The researchers performed frontal, side, rear, and rollover crash tests. The resulting data allowed researchers to reconstruct and publish the "crash pulse" for each crash type. The published crash pulses now allow manufacturers to consistently test seats, cots, equipment mounts, cabinets, and ambulance bodies in highly controlled sled test facilities, which is far less expensive than crashing an entire ambulance.

Many of these partnerships were part of a multiyear collaboration between the U.S. Department of Homeland Security (DHS) Science and Technology Directorate, the National Institute of Standards and Technology (NIST), NIOSH, and over 30 industry partners. For example, in 2011, NIOSH and DHS partnered with six seating and restraint manufacturers to develop new testing methods and performance requirements for ambulance patient compartment seating (NIOSH, 2017a). These efforts culminated in ten new SAE-recommended practice documents that improve the safety of the ambulance patient compartment; two in 2010–2011, four in 2014, and four in 2016–2017.[41] The DHS report lists NIOSH as one of four key partners in developing standards, guidelines, and best practices for ambulance patient compartments (along with NIST, D&P, and Carlow International), and NIOSH is explicitly referenced as "characterizing injury risks associated with ambulances crashes . . . assessing the durability of components in patient compartments, including seats, restraints, cabinets and fastening mechanisms, and drafting specifications that will guide the design and selection of safer patient compartment components" (Avery et al., 2015, p. iv). Industry partners provided equipment and shared the costs associated with the 17 full-vehicle crash tests and over 270 component-specific (cots, seats, equipment mounts, cabinets) sled tests conducted as a part of this program.

The SAE-recommended practice documents produced by this effort provide guidance on many aspects of ambulance safety. For example, SAE J3026 is focused on ensuring ambulance seating meets the same criteria as seating for a car (NIOSH, 2017a), including using the same crash test dummies that are used in the automotive industry. SAE J3059, a companion to SAE J3026, provides methods for measuring how far an occupant's head travels while seated and restrained during each type of crash event. Other standards provide tests for assessing restraints, cots, storage compartments, equipment mounts, and the body of the patient compartment itself. These provide the first crash test requirements for the ambulance patient compartment and the equipment used within it. The crash tests NIOSH conducted in collaboration with manufacturers directly led to those manufacturers changing their designs to meet the new standards. This was accomplished through an iterative process. As testing was conducted, manufacturers would provide new, stronger prototype components as test assets. This iterative process allowed the test procedures to be tested and refined while also providing manufacturers with the opportunity to

[41] For more information, see NIOSH, 2017c, and Avery et al., 2015.

refine and improve new products. This collaboration between NIOSH and manufacturers led to new, safer products becoming available to EMS end users. In summary, the patient compartment of ambulances that meet the new standards are safer in the event of a crash.

The NIOSH impact on ambulance design has not been the result of a single publication or research breakthrough, but rather a steady stream of partnerships with stakeholders, with a focus on improving the design of the patient compartment and its contents, both by working directly with manufacturers and by collaboration with standard-setting organizations. The expenses and overall efforts have been collaborative, as neither industry nor government had the resources or expertise to develop these standards independently.[42] However, one industry representative we spoke with was clear that NIOSH led the development of the SAE standards.[43] Another stakeholder noted that while there are many government agencies and research groups involved in this effort, NIOSH is unique in its focus on worker safety.[44] Table 3.2 lists some of the organizations NIOSH has partnered with to improve safety in ambulance patient compartments. Industry partners are not disclosed in some publications to provide anonymous testing (e.g., Green et al., 2010), which helps enable industry participation. Initial models were not always able to meet the pending standards, and manufacturers modified their designs in response to the results of NIOSH tests. As a result, these partnerships ultimately led to changes in safety for seats, patient cots, equipment mounts, cabinets (storage devices), and ambulance bodies.

Table 3.2. Organizations NIOSH Has Worked with to Improve Safety in Ambulance Patient Compartments

ACC Climate Control	Medix Specialty Vehicles
American Emergency Vehicles	MGA Research Corporation
American Medical Response	Ministry of Health and Long-Term Care, Ontario
ARCCA, Inc.	National Fire Protection Association
Braun Ambulances	National Highway Traffic Safety Administration
Canadian Forces Medical Group	National Institute of Standards and Technology
Center for Advanced Product Evaluation	National Registry of Emergency Medical Technicians
City of Fairfax, VA Fire Department	National Truck Equipment Association
Commission on Accreditation of Ambulance Services	Purcellville, Va., Vol. Rescue Squad
Defense Research Development Canada	Serenity Safety Products
Demers Ambulances	Stryker EMS
E.V.S. Ltd.	Takata
Federal Emergency Management Agency—Mt. Weather	Transportation Research Center
Ferno-Washington, Inc.	U.S. Army Tank Automotive Research, Development and Engineering Center

[42] Assessment based on an interview with Jim Green of NIOSH on June 21, 2019.

[43] Assessment based on an interview with an equipment manufacturer on April 10, 2019.

[44] Assessment based on an interview with an ambulance standards entity on February 27, 2019.

General Services Administration	U.S. DHS Science and Technology Directorate
Horton Emergency Vehicles	U.S. Public Health Service
IMMI	Virginia Department of Health
Intertek Industrial Corp.	Wheeled Coach Ambulances
Life EMS Ambulance	Wise Emergency Medical Seating
Life Line Emergency Vehicles	

SOURCE: NIOSH, 2017a, and communications with NIOSH staff.

Although this chapter focuses on the safety of patient compartment occupants in the event of a crash, NIOSH research on ambulance safety goes beyond this area. For example, NIOSH is exploring the potential of using UV light to help decontaminate the interior of patient compartments after use.[45]

Evidence of Adoption

Each of the ten SAE-recommended practice documents are referenced in the most recent revision of the GSA KKK-A-1822F Purchase Specification for the Star-of-Life Ambulance Standard, the most recent NFPA 1917 Standard for Automotive Ambulances, and the most recent edition of the CAAS GVS. CAAS began the development of their second version or edition on November 7, 2018. Incorporation of these SAE-recommended practice documents into these three sets of standards affects adoption through two related mechanisms. All but six U.S. states have adopted either GSA, NFPA, or CAAS standards. Most ambulance builders have also adopted these standards as their own minimum standards, meaning new equipment sold in states that have not adopted a standard is still likely to meet the those standards. Thus as municipalities and private companies continue to purchase new ambulances, the fleet of U.S. ambulances is being updated with new designs that meet these new, safer standards, based on research that NIOSH initiated and led.

Approach for Estimating the Economic Benefit of Ambulance Design Standards

The ideal data for assessing the potential impact of ambulance design standards are not always available. The methodology below draws on a variety of data sources and imposes several important assumptions to reach an estimate of the potential impact of these design changes.

[45] For more information, see Lindsley et al., 2018.

Step 1: Identify the Target Population

The population targeted by improvements in ambulance design includes two groups that ride in ambulances: EMS workers and the general public. The 2011 National EMS Assessment found that there are 826,000 licensed and credentialed EMS workers in the United States, which includes first responders, emergency medical technicians, paramedics, and others (Mears et al., 2012). The 2018 Current Population Survey estimated there were 240,800 full-time employed EMTs and paramedics (NIOSH, 2019b). In addition to EMS workers, members of the general public ride in the patient compartment as patients or when accompanying a patient.

An alternative way to think about the target population is the number of ambulances that require design changes. Unfortunately, we are not aware of any data sources that definitely count the number of ambulances in the United States. The best available source is the National Association of State EMS Officials (NASEMSO)'s 2011 EMS Industry Snapshot, which asked the director of each state's regulatory EMS office many questions, including how many EMS vehicles of different types were credentialed in their state at that time (Mears et al., 2012). Based on this survey, we estimate there were approximately 75,000 ambulances in the United States in 2011.[46] We do not know the distribution of different types of ambulances.[47]

Step 2: Estimate the Risk Exposure

Different individuals may spend significantly different amounts of time riding in ambulances. For this reason, we estimate the overall risk exposure by estimating the number of ambulance trips taken each year. Unfortunately, there is no data source designed for estimating the total number of ambulance trips made each year; the only relevant existing estimate we are aware of is that EMS providers performed more than 7 million patient transports in 2002 (Proudfoot, Moore, and Levine, 2007), with the authors speculating "the actual number is presumably much higher" (p. 88). This report indeed estimates a much higher value—we estimate there were 36.1 million round-trip ambulance trips in 2016, most of which involve patient transport. Due to data limitations this estimate requires assumptions about the frequency of ground versus air ambulance transportation and the frequency of nonemergency trips. In this section, we draw on

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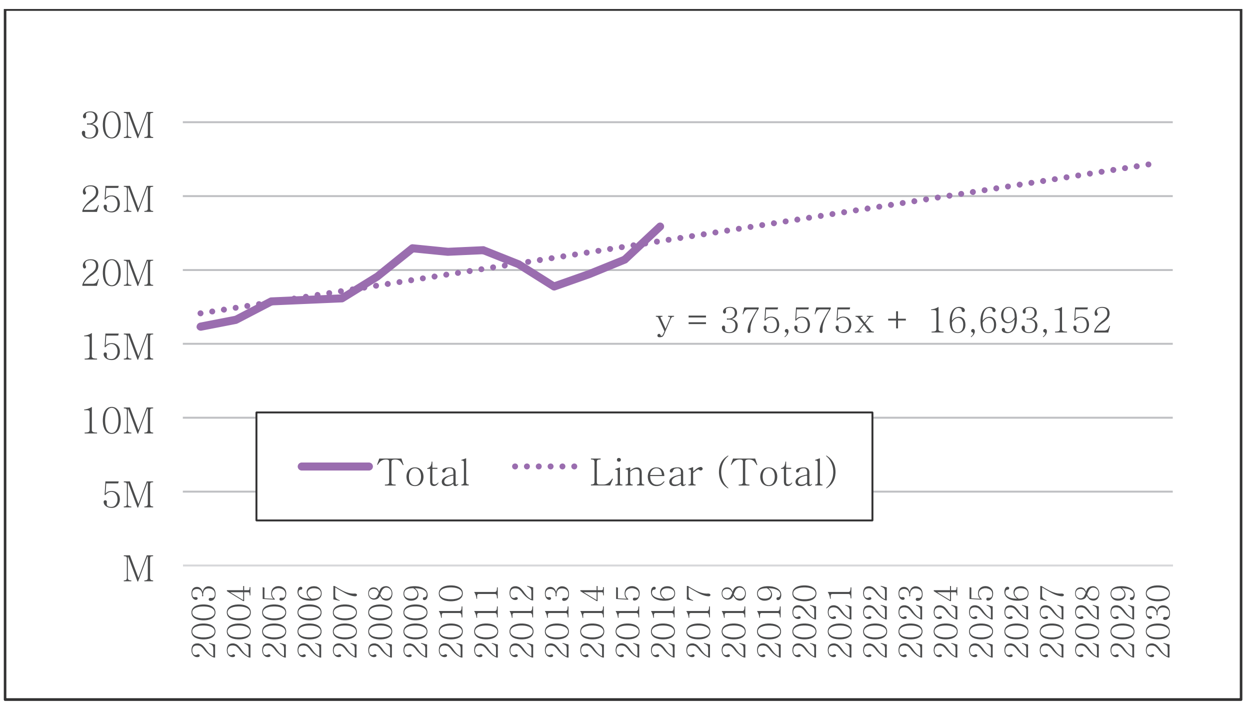
[46] According to Mears et al., 2012, thirty-four states reported having an average of 512.9 basic life support transport vehicles currently credentialed, and 37 states reported having an average of 981.8 advanced life support transport vehicles currently credentialed. The survey separately identifies air medical and boat vehicles, so we assume all of these transport vehicles are ambulances. If the states that did not estimate their number of both types of transport vehicles have the same average number of vehicles as those that do report, and if survey responses provide unbiased estimates of the actual number of ambulances, then in 2011 there were $512.9 \times 50 + 981.8 \times 50 = 74{,}735$ certified ambulances in 2011. The number of trips made by ambulances has grown over time, but we do not know if the number of ambulances has grown in proportion.

[47] There are three main types of ambulances. Type I and Type III ambulances both have a box-shaped patient compartment; Type I is mounted on a truck chassis and Type III is mounted on a van chassis. Type II ambulances do not have a box-shaped patient compartment, but instead use a van chassis with a raised roof.

several data sources to reach reasonable assumptions on these issues. However, we are not able to precisely estimate the total number of individuals riding in the patient compartment of ambulances each year due to data limitations. For this reason, later steps estimate the benefits associated with the new ambulance designs based on the estimated number of future crashes and assumptions about the number and severity of injuries per crash, rather than by estimating the reduction in risk per trip. This means benefit estimates do not rely on the assumptions used to reach our estimate of 36.1 million round-trip ambulance trips in 2016. The purpose of this section is to provide context on the scale of risk exposure, and to provide an updated estimate of the number of ambulance trips per year. To arrive at our estimate of 36.1 million round-trip ambulance trips in 2016, we first use the National Hospital Ambulatory Medical Care Survey (NHAMCS) to estimate the number of patients arriving at emergency departments by ambulance per year, as shown in Figure 3.3. The NHAMCS covers the years 1992–2016. It estimates that 22.9 million patients arrived at hospitals via ambulance in 2016, with 19.4 million (84.4 percent) of these trips ending at hospitals in Metropolitan Statistical Areas (MSAs), and 3.6 million (15.6 percent) of these trips ending at hospitals in non-MSAs. The data also shows the number of trips has been increasing by an average of 375,000 ambulance trips to emergency departments each year. While this is a useful starting point, 22.9 million is an underestimate of the total number of trips that are driven by ambulances each year because not all ambulance trips are to emergency departments, as discussed further below.

Figure 3.3. The Number of Ambulance Trips to Emergency Departments Is Increasing over Time



SOURCE: RAND analysis of NHAMC data.
NOTE: The year 2006 is omitted due to an error in the data.

The NHAMCS data do not specify the type of ambulance; the NIOSH research supported safety designs for ground transportation ambulances, not air transportation. The NHAMCS data do not describe what fraction, if any, of these 22.9 million patient arrivals occur via air ambulance. However, the fraction of recorded ambulance trips that occur via air ambulance is likely very small.[48] Air medical vehicles only make up approximately 2 percent of the EMS transportation vehicles reported to the NASEMSO 2011 EMS Industry Snapshot (Mears et al., 2012). If air transportation is included in the estimate of 22.9 million trips, and if the average air ambulances transport just as many patients per day as the average ground ambulance, then 22.4 million of the trips are ground transportation ambulances. This is a conservative estimate if the average air ambulance is used less frequently than the average ground ambulance.

As noted above, the NHAMCS data only estimate the number of trips to emergency departments. There are other scenarios in which ambulances are being driven, such as transportation between nursing homes and medical appointments, discharge from hospital to home, and transportation between medical facilities. These trips are important to consider when estimating the benefits associated with improved patient compartment safety, as there may be a patient in the patient compartment during nonemergency trips (Proudfoot, Moore, and Levine, 2007). Some nonemergency trips may not involve patient transportation.

While we do not have data for precisely estimating the number of trips made by ambulances in addition to those that occur in the NHAMCS data, a very rough estimate can be made by looking at data from the National Automotive Sampling System–General Estimates Data System (NASS-GES) on whether or not an ambulance was in emergency operation at the time of a crash. As shown in Figure 3.4, NASS-GES estimates there have been 21,265 crashes of ambulances not in emergency operation since 2002, compared with 34,816 crashes of ambulances that are in emergency operation.[49] If we assume that (1) ambulances involved in transporting a patient to an emergency department are in emergency operation, and (2) whether an ambulance is in emergency operation is unrelated to its probability of being in a crash,[50] then the additional number of nonemergency trips being taken by ground ambulances would be

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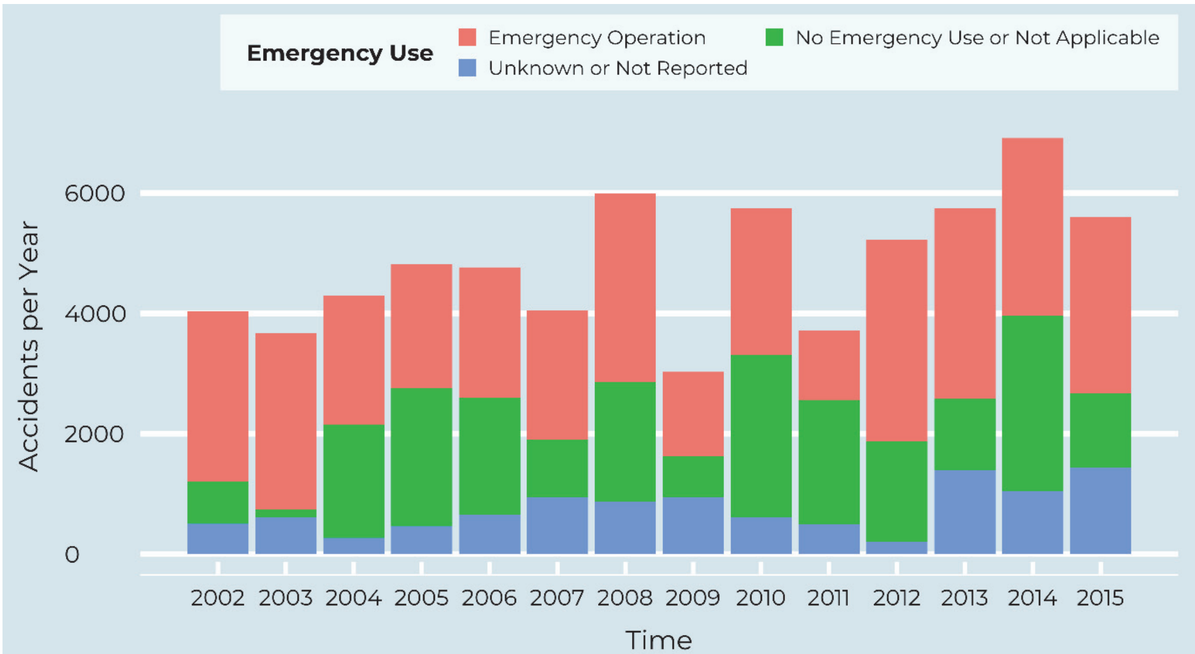
[48] An additional estimated 2.7 million patients arrived via "unknown" methods, and whether the patient arrived by ambulance is unreported for an estimated 0.9 million patients. It is possible that air ambulance trips may be more likely to fall into these categories.

[49] For the purpose of arriving at an estimate of the number of ambulance trips, we assume that cases where emergency use status was "Unknown or Not Reported" is equally likely to be an emergency or nonemergency operation.

[50] The second assumption is partially supported by NASS-GES data showing that in the vast majority of crashes involving ambulances, the speed of the ambulance was not deemed a factor in causing the crash.

22.4 million × 21,265 / 34,816 = 13.7 million. These are likely both imperfect assumptions but are preferable to ignoring nonemergency trips altogether.[51]

Figure 3.4. The Emergency Status of Ambulances Involved in Crashes Varies



SOURCE: RAND analysis of NASS-GES data.

The assumptions outlined in this step are the basis for this report's estimates that there were approximately 36.1 million (22.4 million + 13.7 million) ambulance trips in 2016.

Step 3: Estimate the Current Rate of Injuries and Fatalities in the Patient Compartment

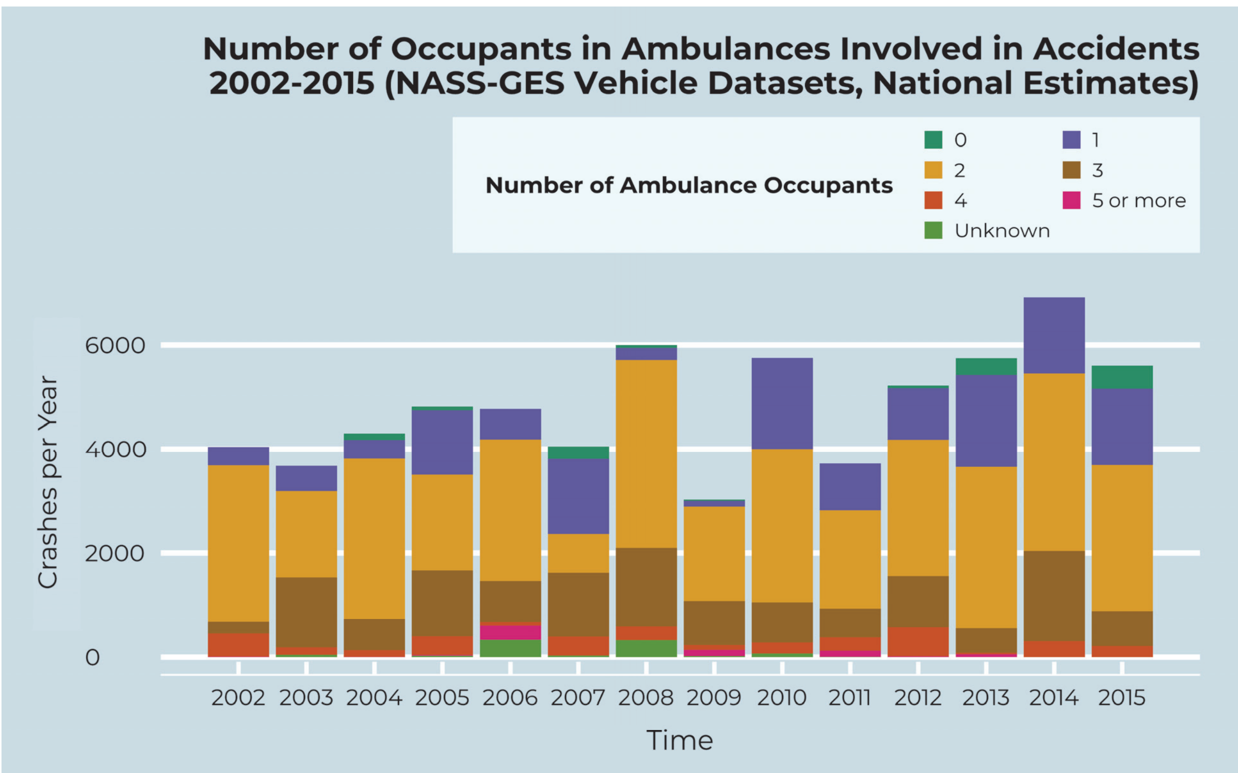
We use data from NASS-GES and FARS to measure the current rates of injuries and fatalities among ambulance passengers, specifically those in the patient compartment. Because our analysis is based on injuries that are recorded in police records of crashes, our analysis does not consider injuries that occur during hard braking or other hazardous maneuvers that do not result in a crash. Injury severity in this data is determined by law enforcement based on the "KABCO" scale, and may not reflect a diagnosis from a medical professional. The categories of

[51] To emphasize the importance of considering nonemergency trips, four of the NHTSA investigations on which NIOSH participated, each involving at least one fatality, were operating in nonemergency transport mode.

injuries in this scale are "fatal injury," "suspected serious injury," "suspected minor injury," "possible injury," and "no apparent injury."[52]

We begin by examining the number of occupants an ambulance typically has at the time of a crash, and where those occupants are located. Figure 3.5 shows that most crashes occur when there are only one or two occupants of the ambulance, including the driver.[53] These crashes may not have any occupants in the patient compartment because emergency transportation of patients typically involves at least three passengers—a driver, an EMS worker in the patient compartment, and the patient.

Figure 3.5. Most Crashes Occur When There Are One or Two Occupants in the Ambulance



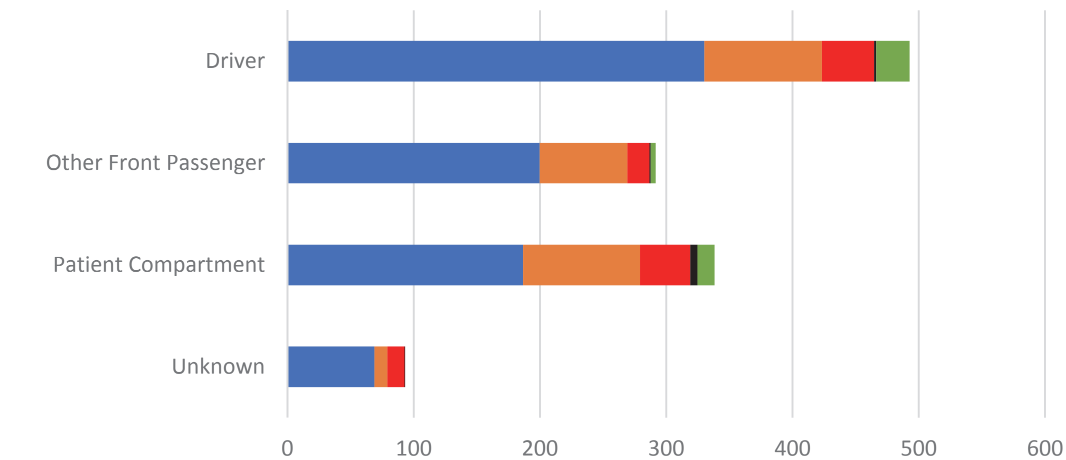
SOURCE: RAND analysis of NASS-GES data.

[52] Precise definitions of KABCO scale injury severity follow the Model Minimum Uniform Crash Criteria, 4th Edition; see NHTSA, undated. Fatal injuries are injuries that result in death within 30 days. Suspected serious injuries may include severe lacerations that expose underlying tissues/muscles/organs, significant blood loss, broken or distorted extremity (arm or leg), crush injuries, paralysis, or unconsciousness when taken from crash scene. Minor injuries include lumps, abrasions, bruises, or lacerations that do not expose deeper tissue/muscle/organs. Possible injuries are "those which are reported by the person or are indicated by his/her behavior, but no wounds or injuries are readily evident," such as momentary loss of consciousness, limping, or self-reported pain or nausea.

[53] In some cases, an ambulance that is stopped or parked may be involved in a crash, so there are a small number of crashes that involve an ambulance with no occupants.

Indeed, Figure 3.6 shows that the majority of injured ambulance occupants are drivers; there were an estimated total of 491 ambulance drivers injured and an average of 1.6 ambulance drivers killed per year from 2002 to 2015.[54] An estimated additional 291 front seat ambulance passengers were injured and an average of 1.1 killed per year from 2002 to 2015. Patient compartments accounted for an estimated 332 injuries and an average of 5.8 fatalities per year. This may undercount the number of patient compartment injuries and fatalities because the distribution of injury severity for the additional 93 injuries and 0.6 fatalities per year that have an unknown seating location more closely resembles the patient compartment than the front seat. Depending on the fraction of injuries with unidentified seating locations that occur in the patient

Figure 3.6. Average Number of Injuries and Fatalities per Year in Ambulances by Seating Location and Severity of Injury, 2002–2015



	Unknown	Patient Compartment	Other Front Passenger	Driver
Possible Injury	69	187	200	330
Minor Injury	10	93	69	93
Serious Injury	14	40	18	41
Fatal Injury	0.6	5.8	1.1	1.6
Injured, Unknown Severity	0	13	4	27

Possible Injury Minor Injury Serious Injury Fatal Injury Injured, Unknown Severity

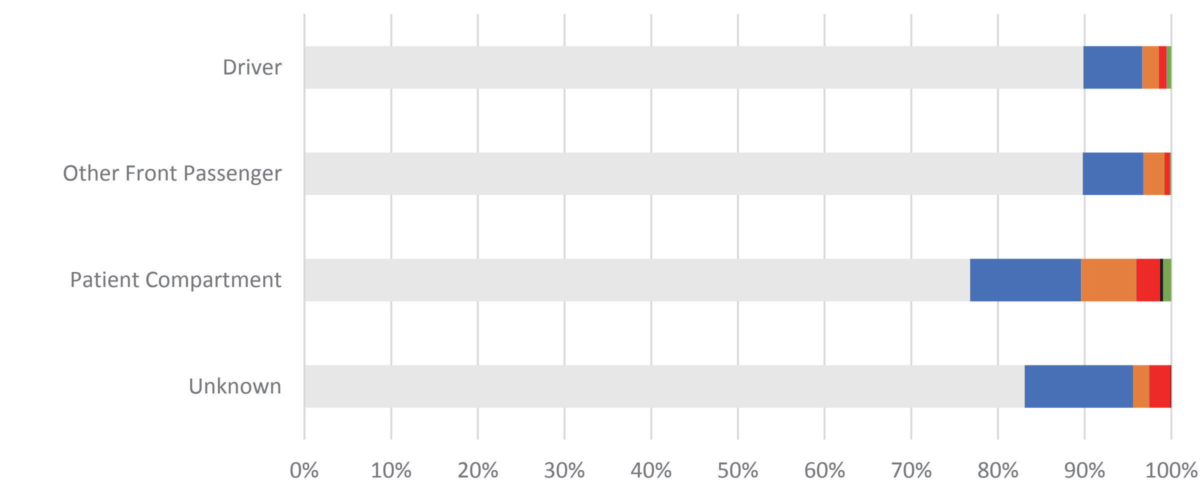
SOURCE: RAND analysis of NASS-GES and FARS data.

[54] Injuries per year are estimated based on nationally representative data. Fatalities per year are based on recorded fatalities, and are not estimates.

compartment, 27.5 percent to 35 percent of injuries that occur in ambulances during motor vehicle crashes occur in the patient compartment. However, 63.8 percent to 70.1 percent of fatalities occur in the patient compartment.

While most injuries occur in the front seat of the ambulance, this does not mean the front of the ambulance is less safe. There are more front seat injuries simply because the patient compartment is empty in many crashes, but there is almost always a driver in the ambulance at the time of a crash. Indeed, Figure 3.7 shows that conditional on being involved in a crash, occupants riding in the patient compartment are significantly more likely to be injured or killed.

Figure 3.7. Distribution of Injury Status by Location in Vehicle Conditional on Crash Occurring, 2002–2015



	Unknown	Patient Compartment	Other Front Passenger	Driver
No Injury	83%	77%	90%	90%
Possible Injury	12%	13%	7%	7%
Minor Injury	2%	6%	2%	2%
Serious Injury	2%	3%	1%	1%
Fatal Injury	0%	0%	0%	0%
Injured, Unknown Severity	0%	1%	0%	1%

No Injury ■ Possible Injury ■ Minor Injury ■ Serious Injury ■ Fatal Injury ■ Injured, Unknown Severity

SOURCE: RAND analysis of NASS-GES and FARS data.

Severe injuries are much less common than "possible" and "minor" injuries. This distribution of injuries in part reflects the distribution of the extent of damage to the ambulance. Crashes most commonly result in minor or moderate damage to the ambulance. Injuries are indeed more severe when the ambulance is traveling faster, although high-speed crashes are rare. Some crashes occur when the ambulance is at a complete stop and is struck by another vehicle.

We estimated urban and nonurban injury rates separately,[55] but we found the probability of injury to be quite similar in urban and nonurban areas, although nonurban rates were less stable due to the small sample size. Fatalities in the patient compartment are a notable exception. Urban areas account for the vast majority of crashes and trips, but crashes in nonurban areas account for five out of nine patient compartment fatalities per year. For these reasons, when estimating the number of avoided injuries and fatalities in Step 4, we assume the only difference between the distribution of injuries in urban and nonurban areas is that patient compartment fatalities are relatively more likely in nonurban areas. Although the distributions are similar, Step 4 multiplies these distributions by the number of ambulance occupants involved in crashes urban versus rural areas. These distinctions are important because the benefits of the ambulance redesign are likely to reach urban areas first, as interviews with multiple stakeholders confirmed that ambulances are replaced more quickly in urban areas due to higher call volume resulting in a higher number of miles driven per year.

Forecasting the number of future occupants involved in crashes is a prerequisite to forecasting the number of future injuries and fatalities.[56] On average, the total number of ambulances occupants involved in a crash has been slowly increasing over time. We assume that, from 2015 forward, the number of ambulance occupants involved in crashes will continue to grow at rate equal to recent population growth, as shown in Figure 3.8. The number of ambulance occupants involved in crashes in urban areas is projected to grow by approximately 80 per year. The number of ambulance occupants involved in crashes in rural areas is projected to remain relatively flat because population growth in rural areas is projected to be near zero.[57] Because the NIOSH research focused on design changes that support patient compartment safety, we estimate the percentage of ambulance occupants that are located in the patient compartment. In both urban and nonurban settings, based on NASS-GES data from 2002 to

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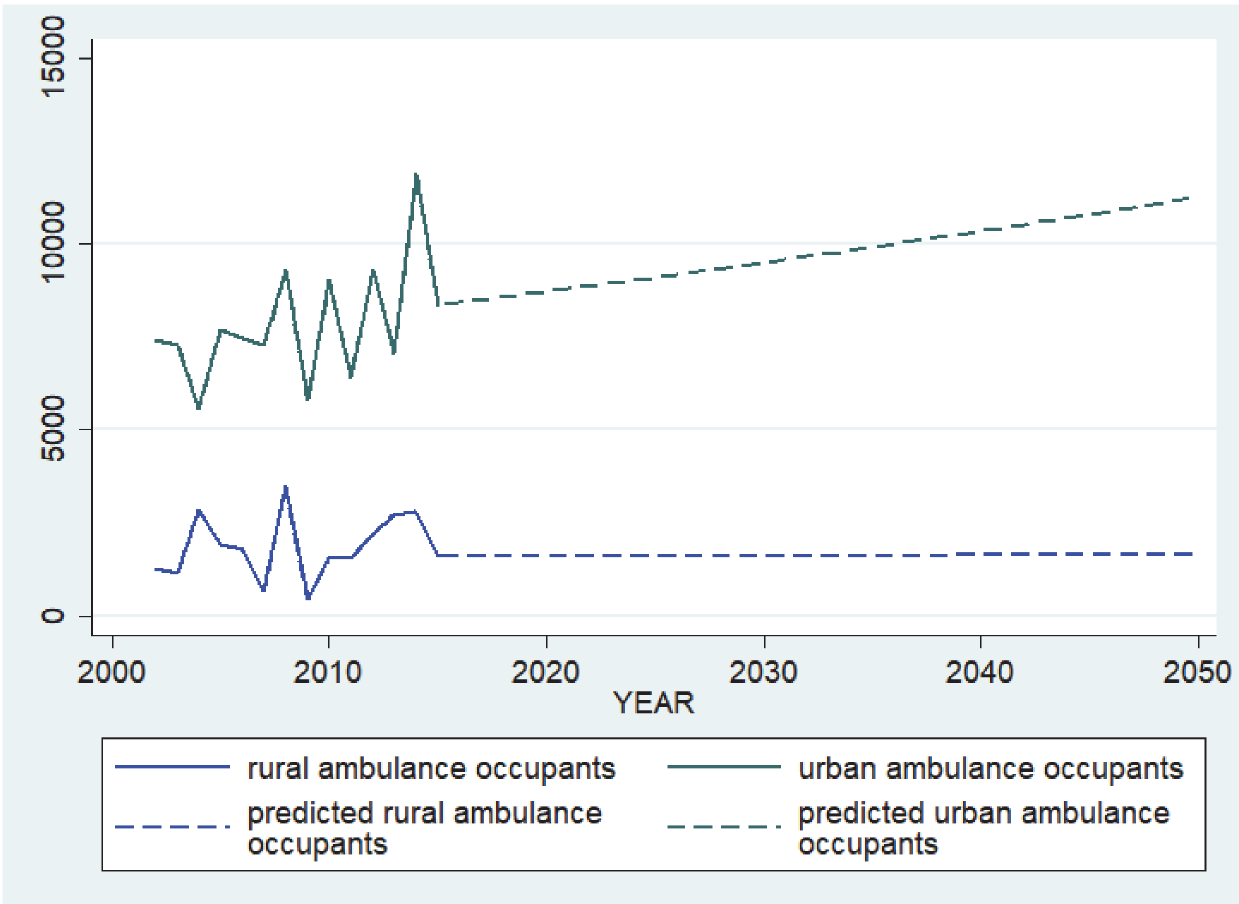
[55] Specifically, the NASS-GES data we use for assessing injuries are collected from a sample of police reports, and we received a cross-walk from NASS-GES identifying which regions are MSAs. We categorized the MSA areas as "urban." We combined areas labeled as "non-MSA" and "both" and call this area "nonurban," because small sample sizes cause estimates to be unstable if these groups are counted separately. For fatalities, the FARS data is not collected from specific police reports, but rather classifies whether the road on which the crash occurred is urban or rural. We categorize crashes that occur on urban roads as attributed to "urban" areas, and crashes that occur on rural roads as attributed to "nonurban" areas. These allocations are imperfect and hence introduce uncertainty, but represent the most reasonable assumptions we can make with the available data.

[56] Our estimate of the number of ambulance occupants involved in crashes is measured in terms of the number of affected-person trips. In other words, we are measuring the total number of occupants in the patient compartment across all ambulance crashes in a year; if the same person is involved in two crashes they are recorded twice. Individuals such as EMS workers may ride in the patient compartment of an ambulance frequently, and hence are exposed to additional risk.

[57] Specifically, we assume a 0.1 percent growth rate for rural areas (following Cromartie and Vilorio, 2019), and a 0.86 percent growth rate for urban areas (following World Bank, 2018).

2015, we estimate that 16 percent of the occupants from 2002 to 2015 were in the passenger compartment, and we assume this ratio remains constant over time.[58]

Figure 3.8. Actual and Projected Number of All Ambulance Occupants Involved in Crashes, by Urban/Rural Status



SOURCE: RAND Analysis of NASS-GES data.

Step 4: Estimate the Potential Number of Avoided Injuries and Fatalities

Step 3 estimated the current number of injuries and fatalities, the distribution of injury severity, and how these vary between urban and nonurban areas. The new ambulance designs are

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[58] Specifically, we find that, after setting aside individuals with unknown seating positions, 15.3 percent of urban occupants were in the passenger compartment and 18.1 percent of rural occupants were in the passenger compartment. We are not aware of any reason to expect a systematic difference between the two settings, and the overall rate is 15.9 percent. We use a percentage of the all ambulance occupants because year-by-year seating position records are very noisy. Small changes in this assumption can result in meaningfully different estimates of total benefits.

intended to reduce the number of injuries and fatalities in the patient compartment, and to reduce the severity of injuries that do occur. The purpose of this case study is to estimate the monetary value of these benefits. We need to first estimate the injury and fatality reductions that are anticipated to occur in the future.

As discussed in the section "Overview of NIOSH's Activities in Ambulance Design," NIOSH has helped conduct and study the results of many crash tests and sled tests to inform these individual design changes. For an example, Green et al. (2010) test the impacts of alternative restraints in a representative ambulance patient compartment interior, and their results highlight the importance of considering all the redesign elements in aggregate. The alternative restraints were more successful than traditional lap belts in preventing injuries, but in some cases testing dummies still contacted other interior elements of the ambulance during crash simulations. Based on that information and many other tests, subsequent redesigns continuously changed elements such as the location of cabinets, the design of the EMS worker's seat, and how the patient cot attaches to the frame of the ambulance. Interviews confirmed that the design changes were holistic explorations of how to improve ambulance patient compartment safety.

Laboratory testing provides critical information on how to improve the design of individual elements, but the ultimate changes in injury and fatality outcomes will depend on many factors. Even though ambulance builders have increased their minimum production standards, communities still face choices about what additional features to purchase, and the effectiveness of the new safety features depends in part on how those in the patient compartment use the new features. It is important to highlight that NIOSH work includes more than changing physical ambulance designs; there has also been significant outreach to change cultural attitudes. EMS workers frequently do not wear restraints, even when these do not interfere with any job functions (NIOSH, 2017a). NIOSH has produced videos and infographics to encourage the use of restraints.

For these reasons, we draw on research literature and NIOSH's stated objectives to identify several alternative estimates of how the redesign might change the severity of injuries that occur in the patient compartment. In each case, we assume that the changes do not reduce the number of crashes; they only alter injury and fatality outcomes in the event of a crash. We also assume the benefits do not accrue until the region has purchased new ambulances.[59] Ambulances are replaced at different rates in different locations because they are driven with different frequencies. Based on interviews, we assume the oldest 25 percent of the ambulance fleet is

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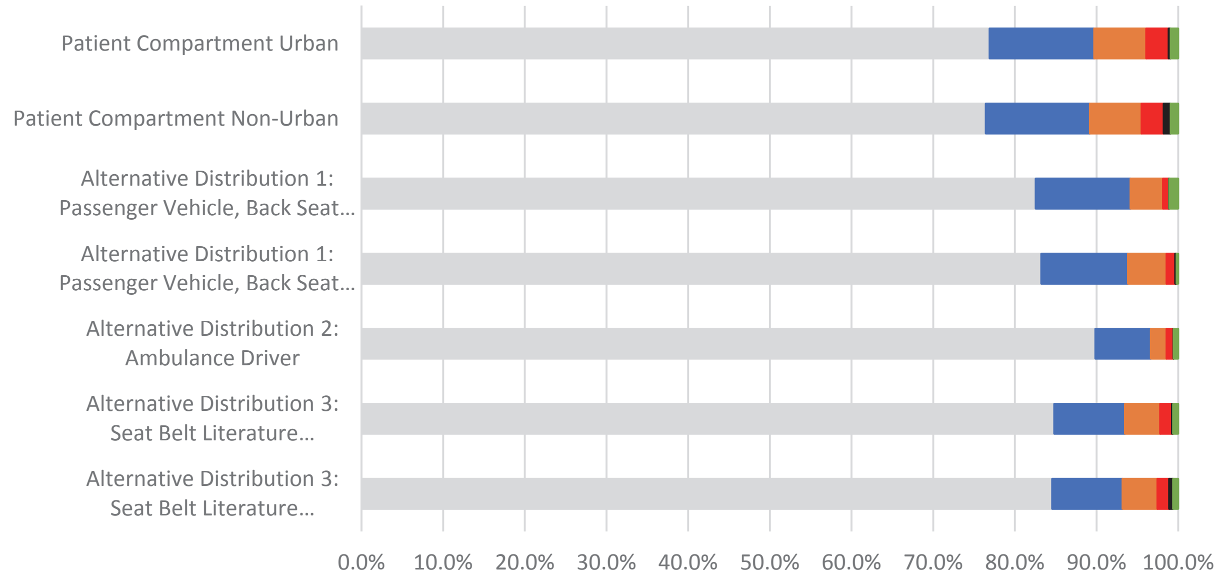
[59] In some cases, the patient compartment "box" is removed from the old truck chassis and is then installed on a new truck chassis. These are called remounts and they are largely unregulated. Remounts generally do not update the patient compartment to meet the new standards, and therefore do not result in a safer patient compartment. Medical transport providers may pursue a remount because it is cheaper than purchasing a new ambulance. We do not have any information about the frequency of remounts relative to new ambulance purchases.

replaced each year in urban areas (i.e., ambulances are replaced every four years), and the oldest 5 percent of the ambulance fleet is replaced each year in nonurban areas (i.e., ambulances are replaced every 20 years). These differences in replacement rates are caused by differences in usage rates; urban ambulances accumulate miles far faster than rural vehicles due to more frequent usage. Based on the date SAE standards were issued and the fact that redesigned ambulances are now available, we assume redesigned ambulances first became available in 2017.

This step identifies three possible alternative injury status distributions that could be associated with the new ambulance design: (1) the current distribution for occupants in the back seat of a standard four-door passenger vehicle, (2) the current distribution for ambulance drivers, and (3) reducing the ambulance patient compartment distribution based on the broader literature on seat belt effectiveness. These alternative injury status distributions are shown in Figure 3.9 and discussed further below. As noted in Step 3, these only reflect injuries that occur during crashes, and do not include injuries that occur during successful crash avoidance maneuvers or other sudden maneuvers, stops, or accelerations. Although we do not have direct information on the number of noncollision injuries, these may not be trivial. Federal Transit Administration data from 2001 on injuries among passengers of metro buses—another large vehicle in which passengers are often unrestrained—shows there are approximately seven noncollision "inside of vehicle" injuries for every ten collision-related injuries (Federal Transit Administration, 2001).[60] The Federal Transit Administration data do not include information on the severity of these noncollision injuries. We cannot state with certainty whether similar rates of noncollision injuries would apply to ambulances.

[60] More recent data from individual metro areas report similar ratios (e.g., Washington Metropolitan Area Transit Authority, 2015). Zunjic et al., 2012, find that most noncollision bus injuries in Belgrade are due to acceleration or deceleration events. Similarly, a NIOSH expert we interviewed reported that anecdotal evidence suggests nonserious injuries caused by crash avoidance maneuvers, such as hard braking, are common because EMS workers are commonly working unrestrained in the patient compartment. Anecdotal evidence also suggests these injuries go unreported because the EMS workers provide their own medical care.

Figure 3.9. Overall Patient Compartment Injury Status Distributions and Alternative Future Distributions, by Rural and Urban Status



	Alternative Distribution 3: Seat Belt Literature (Non-Urban)	Alternative Distribution 3: Seat Belt Literature (Urban)	Alternative Distribution 2: Ambulance Driver	Alternative Distribution 1: Passenger Vehicle, Back Seat (Non-Urban)	Alternative Distribution 1: Passenger Vehicle, Back Seat (Urban)	Patient Compartme nt Non-Urban	Patient Compartme nt Urban
No Injury	84.6%	84.8%	89.9%	83.2%	82.5%	76.4%	76.9%
Possible Injury	8.6%	8.7%	6.8%	10.6%	11.6%	12.7%	12.8%
Minor Injury	4.3%	4.3%	1.9%	4.7%	4.0%	6.3%	6.4%
Serious Injury	1.4%	1.5%	0.9%	1.1%	0.7%	2.7%	2.7%
Fatal Injury	0.5%	0.1%	0.0%	0.2%	0.0%	0.9%	0.3%
Injured, Unknown Severity	0.6%	0.6%	0.5%	0.2%	1.1%	0.9%	0.9%

No Injury Possible Injury Minor Injury Serious Injury Fatal Injury Injured, Unknown Severity

SOURCE: RAND analysis of NASS-GES and FARS data, and modeling assumptions based on NHTSA, 2000, and Cummings, Wells, and Rivara, 2003.

For the first alternative injury status distribution, we assume new ambulances have a patient compartment injury status distribution that is identical to the current distribution for the back seat of a standard four-door passenger vehicle. The reason we examine this alternative injury distribution is because the overall goal of these design changes is to make the back of the ambulance as safe as a typical car (NIOSH, 2017a). This alternative injury distribution estimates the benefits associated with achieving that goal. We use the distribution of injury types from the back seat of a standard four-door passenger vehicle measured using the same 2002–2015 NASS-GES data,[61] separately estimating the injury distribution for urban and nonurban settings. Like ambulances, the risk of fatality is slightly higher in nonurban settings, although there is still a significant decrease in fatalities.

For the second alternative injury distribution, we assume new ambulances have a patient compartment injury status distribution that is identical to the driver of the ambulance.[62] The reason we examine this alternative injury distribution is because it represents an injury distribution associated with the same vehicles and similar individuals, but injury outcomes associated with more traditional safety settings. This is important because ambulances are driven very differently from passenger vehicles, and as a result may be involved in very different types of collisions. This alternative injury distribution estimates the benefits associated with making the patient compartment as safe as the front of the ambulance. This alternative injury distribution does not vary by urban versus rural status because, as noted in Step 3, we cannot estimate the distribution of injuries separately for urban versus nonurban ambulances, and the sample size for fatalities among ambulance drivers is too small to accurately measure a difference between urban and nonurban regions.

For the third alternative injury distribution, we assume new ambulances reduce the number of injuries in each severity category by a fixed percentage. The standards introduced by NIOSH, as well as the design changes made by the manufacturers NIOSH partnered with, made a wide variety of changes to improve the safety of the patient compartment. Broadly, these changes include (1) improving the effectiveness of restraints and their compatibility with worker tasks; (2) ensuring other contents of the ambulance, ranging from the patient cot to equipment, are secured to avoid becoming projectiles; and (3) rearranging interior compartments and/or padding surfaces to reduce the risk associated with patient compartment occupants striking these surfaces. NIOSH's tests resulted in some of the first publications on the risks associated with old and new designs, but the literature is too nascent for us to definitely model exactly what reduction in injuries will result. We attempted to focus specifically on the benefits associated with restraints given the larger literature on this topic, and we present those efforts, although we ultimately conclude that this approach involves significant amounts of uncertainty.

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[61] Using the injury distribution for drivers instead of back seat passengers makes little difference, because the overall difference in risk between the back seat of a car and the driver of a car is small compared with the difference in risk between a car and an ambulance. We a priori chose the back seat because, like the patient compartment of an ambulance, occupants do not face significant risk of ejection in a collision.

[62] Another suggestion was to assume the patient compartment is as safe relative to the front of the ambulance as the back seat of a passenger car relative to the driver of a passenger car. The results would be fairly similar to the ones we present, again because the overall difference in risk between the back seat of a car and the driver of a car is small compared with the difference in risk between a car and an ambulance.

The Road Safety Observatory (2018) provides an excellent overview of the literature on seat belt effectiveness. Although it is widely agreed that using a seat belt decreases the risk of injury, different studies examining different locations, times, vehicles, seating positions, and types of restraints have reached different conclusions about the effectiveness of seat belts in preventing injuries. To our knowledge, no ambulance-specific estimates are available, and it may be difficult to re-create others' methods due to the relatively small sample size of collisions involving ambulances relative to other types of vehicles. To proceed, we are required to select the most relevant and reasonable estimates from the literature, emphasizing that alternative assumptions could yield different results.

Robertson (1976) points out that early estimates of effectiveness ranged from less than 10-percent reduction in fatalities to over 80-percent reduction in fatalities. We base our assumption for fatality risk on two more recent studies. NHTSA (2000) found seat belts reduce fatalities in light trucks by 60 percent, with uncertainty ranging from +/– 4 percentage points to +/– 10 percentage points. Because many ambulances are built on truck frames, we assume the estimate of a 60-percent reduction in fatalities is more relevant. Another particularly relevant study is Cummings, Wells, and Rivara (2003), which also examines fatalities using the FARS database, and also finds that approximately 60 percent of unrestrained occupants would have survived if properly restrained.

Estimates on the effectiveness in preventing nonfatal injuries also vary widely. NHTSA (1984) found that restraints reduced moderate to critical injuries in light trucks by 65 percent. This seems to be the most relevant estimate from the literature, but we emphasize that estimates vary. A meta-analysis of the seat belt effectiveness literature by Elvik et al. (2009) found that for cars and vans, seatbelts were 40–50 percent effective in reducing serious injuries, and 20–30 percent effective in preventing minor injuries, with seatbelts being slightly less effective at preventing injuries in rear seats. Ultimately, based on NHTSA (2000) and Cummings Wells, and Rivara (2003), we assume that seat belt use reduces fatalities by 60 percent. Based on NHTSA (1984), we assume that seat belt use reduces serious injuries by 65 percent. Based on Elvik et al. (2009), we assume that seat belts are 20 percentage points less effective at preventing minor, possible, and unknown severity injuries in ambulances; we assume those injuries are reduced by 45 percent.

As discussed in the introduction of this chapter, only 16 percent of EMS providers in the patient compartment were restrained at the time of the crash (Smith, 2015). One older survey found that 55 percent of EMS personnel reported that they would use restraints if they allowed for mobility (Larmon, LeGassick, and Schriger, 1993), although those we spoke with at NIOSH hope the usage rate will be closer to 100 percent in practice. NHTSA (undated-b) estimates that the overall usage rate of seat belts in the United States was 89.6 percent in 2018. Further, as noted in the introduction of this chapter, patients are almost always restrained, however three-point harnesses are often not available. The seat belt effectiveness literature finds that lap belts are significantly less effective than three-point belts, and NIOSH's own research clearly shows that the new restraints are superior to prior designs. Hence this alternative distribution faces further uncertainty because we lack recent information on the extent to which those in the patient compartment (both EMS workers and other passengers) will be properly restrained. We also do not have sufficient data to differentiate between patients and workers in modeling reductions in injury associated with new restraint designs. As such, we make the following simplifying assumption: We assume that 35 percent of patient compartment occupants were restrained by an old design[63] and that occupants of the new patient compartment designs will match the national average usage rate of 89.6 percent. Based on rough comparisons of the effectiveness of lap belts to three-point harnesses described by the Road Safety Observatory, we assume those who go from wearing the old restraints to the new designs experience 50 percent of the reduction in injury risk experienced by those who go from no restraint to the new designs.

We maintain a distinction between urban and nonurban outcomes in this alternative distribution because we have simply scaled the original urban and nonurban outcomes. We view this particular alternative distribution as a largely illustrative exercise that shows where further research is required, and we emphasize that it does not incorporate the many changes to ambulance patient compartments that extent beyond seat belts.

Next, we calculate the change in injuries over time associated with each alternative distribution. For each alternative injury distribution, we count the number of the various types of injuries by multiplying the forecasted count of ambulance patient compartment passengers by the probability associated with each injury category. Figure 3.10 provides a visualization of this information, from 2015 through 2050, showing the total number of avoided injuries per year of any type associated with each of the alternative distributions.[64] Figure 3.10 includes all injury severity categories. The number of injuries in each category in any given year match the distributions presented in Figure 3.9. For all three alternative distributions, there is an initial steep prevention of injuries as urban areas update their ambulance fleet. This rate then slowly continues to rise while nonurban areas update their fleet, which under our modeling assumptions will be complete in 2036. Avoided injuries continue to rise slowly after that point solely due to population growth.

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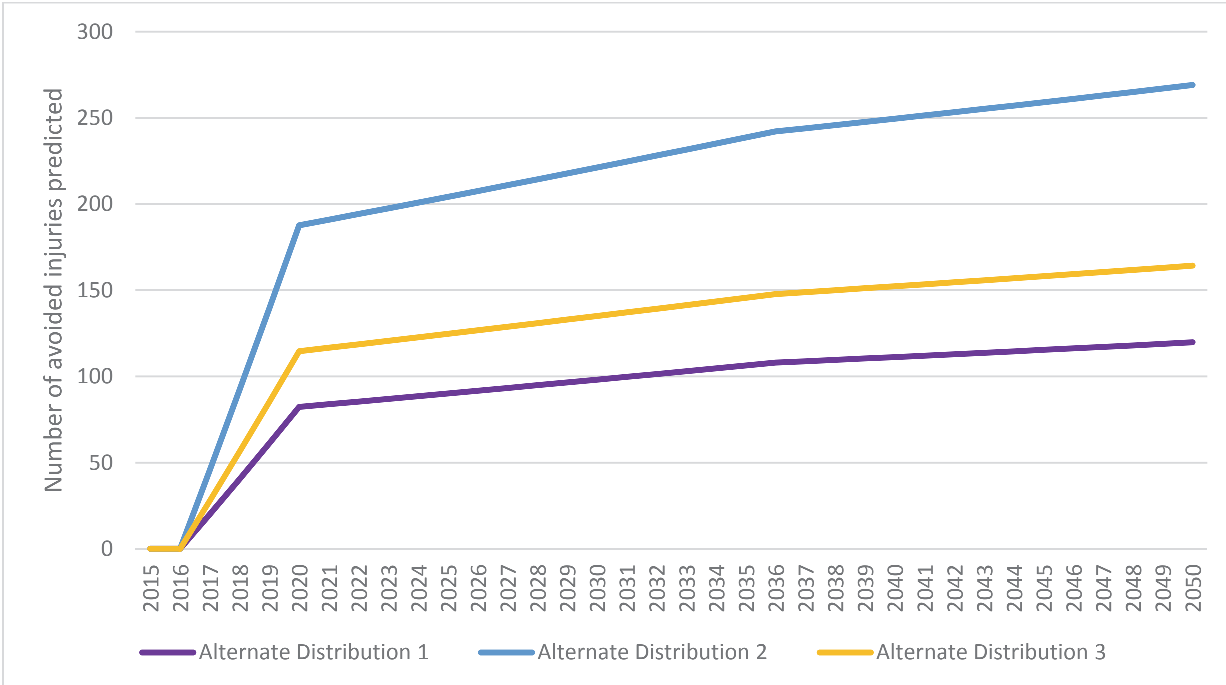
[63] The precise number of patient compartment occupants is not known. We suppose the average patient compartment occupants are two EMS workers en route to pick up the patient, and two EMS workers plus the patient en route to a hospital. If the EMS workers are always restrained 16 percent of the time, and the patient is restrained 96 percent of the time, then the average occupant is restrained roughly 35 percent of the time.

[64] We choose this time period to highlight the three distinct periods of this model. The first where benefits increase due to urban fleet updates, nonurban fleets updates, and population growth, the second where benefits increase due to nonurban fleets updates and population growth, and the third where benefits increase due to population growth only.

Figure 3.10. Avoided Injuries per Year Will Increase as New Ambulances Become More Prevalent over Time



Consistent with Figure 3.9, if redesign results in the patient compartment becoming as safe as the front of the ambulance, this would achieve the largest reductions in future injuries of the three examined objectives. If the redesign results in the back of the ambulance becoming as safe as the back of a passenger vehicle, this would achieve the smallest reduction in future injuries. This report does not assess the probability that the designs will achieve these objectives or potential future reductions in injuries and fatalities.

Step 5: Monetize Avoided Injuries and Fatalities

We conclude by estimating the value of these potential reductions in injuries and fatalities in terms of both direct costs (wage and productivity losses, medical expenses, administrative expenses) and in terms of the WTP to avoid these injuries, as measured by VSL, following values provided by the National Safety Council (NSC) (Injury Facts, 2017).[65] Specifically, we treat direct costs and VSL, as shown in Table 3.3. We conservatively assume that injuries of

[65] The NSC estimates include motor vehicle damage and administrative costs that occur regardless of whether injuries occurred. To focus on injury-related costs, we subtract the NSC cost estimates associated with no injuries from the NSC estimates for the other categories. We may still overestimate costs if costs unrelated to injury are higher in cases where injuries occur. We note that NSC's VSL values for a fatality are slightly larger than the DOT VSL values used in Chapter 2.

unknown severity are equivalent in cost to possible injuries. As noted in Step 4, these values do not include injuries associated with noncollision events.

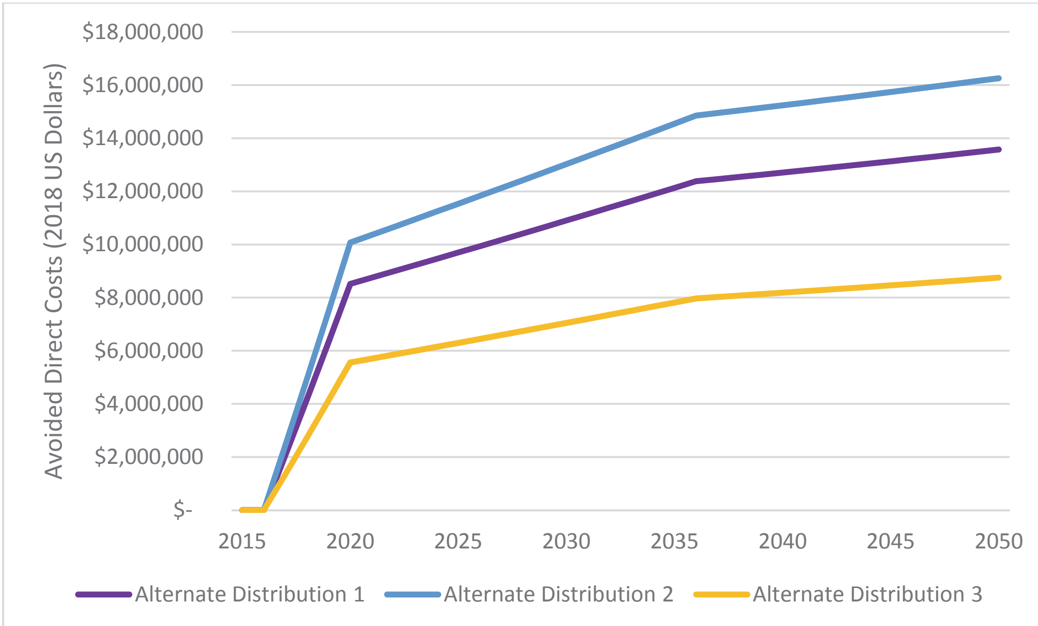
Table 3.3. Direct Costs and VSL Values (2018 U.S. Dollars)

Injury Category	Direct Costs	VSL
Fatal Injury	$1,636,292	$10,730,979
Serious Injury	$83,596	$1,129,206
Minor Injury	$15,515	$274,876
Possible Injury	$10,615	$100,335
Unknown Severity	$10,615	$100,335
No Injury	$0	$0

SOURCE: Derived from Injury Facts, 2017.
NOTE: Inflation adjustments follow Bureau of Labor Statistics (BLS) calculations based on CPI.

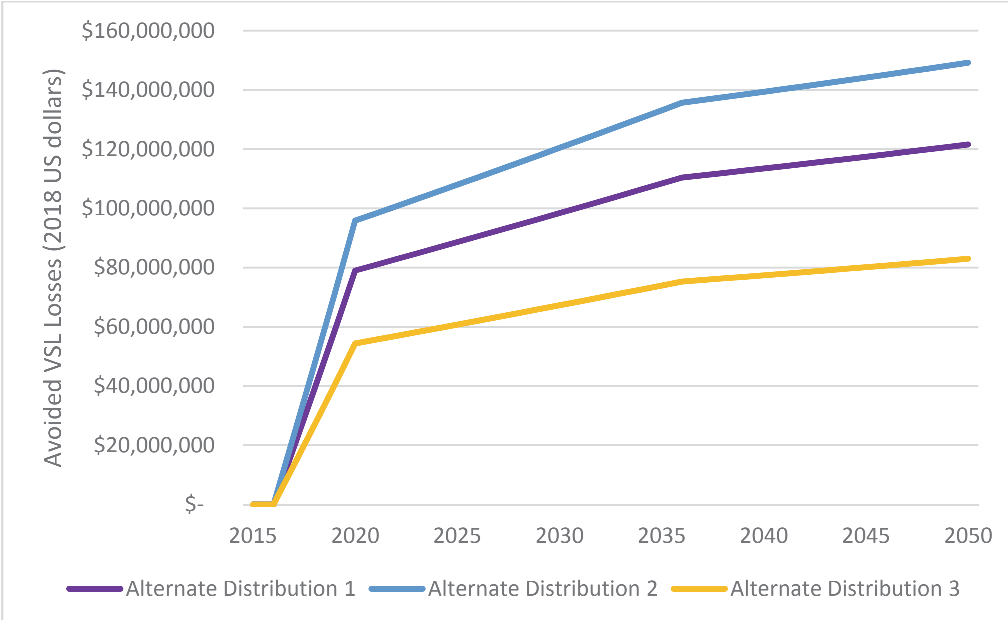
These differences in cost mean the total number of injuries avoided is not the only factor in determining the overall monetized savings; the type of injury avoided also matters. Although Figure 3.10 showed that Alternative Distribution 1, based on the injury distribution of a passenger vehicle, results in the least injury reduction of the three alternatives considered, it also assumes the largest decrease in fatal injuries. Figure 3.11 shows that if the ambulance redesign causes the patient compartment of ambulances to become as safe as any of these alternative distributions, this could result in $5.6 million to $10.1 million per year in avoided direct costs by 2020, and $8.0 million to $14.9 million by 2036. For comparison to the case presented in Chapter 2, these result in an annualized value of $4.3 million to $8.0 million from 2017 to 2050 at a 3-percent discount rate, and an annualized value of $2.5 million to $4.6 million from 2017 to 2050 at a 7-percent discount rate. Figure 3.11 does not incorporate a discount rate. We emphasize the many uncertainties associated with these alternative distributions means the ultimate impact could vary significantly, with Alternative Distribution 2 providing an upper bound if it is unlikely for the patient compartment to become significantly safer than the front of the ambulance.

Figure 3.11. Total Avoided Direct Costs per Year Will Increase as New Ambulances Become More Prevalent over Time (2018 U.S. Dollars)



VSL estimates follow a similar pattern, although they reflect larger societal costs associated with injuries and fatalities. Figure 3.12 shows the modeling assumptions in this report suggest that if the ambulance redesign causes the patient compartment of ambulances to become as safe as any of these alternative distributions, this could result in $54 million to $96 million per year in avoided VSL losses by 2020, and $75 million to $136 million by 2036. For comparison to the case presented in Chapter 2, these result in an annualized value of $41 million to $74 million from 2017 to 2050 at a 3-percent discount rate, and an annualized value of $24 million to $43 million from 2017 to 2050 at a 7-percent discount rate. Figure 3.12 does not incorporate a discount rate. Again, we emphasize the many uncertainties associated with these alternative distributions, and that Alternative Distribution 2 may provide an upper bound.

Figure 3.12. Total Avoided VSL Losses per Year Will Increase as New Ambulances Become More Prevalent over Time (2018 U.S. Dollars)



Conclusion

Patient compartments accounted for an estimated 332 injuries and an average of 5.8 fatalities per year from 2002 to 2015. This case study focuses on the benefits of this research to the U.S. population, but it is important to note that this research may also benefit citizens of other countries. Other countries each have their own ambulance design standards. Other countries may adopt the same SAE standards that are based on NIOSH research, rather than re-creating the same research themselves. Indeed, some of the industry partners NIOSH worked with are encouraging Canada to adopt the same SAE standards, as common global standards can help companies streamline manufacturing processes.

This report provides estimates of the benefits that would be achieved under three different objectives or potential changes in the safety of the patient compartment. This report does not assess the probability that the designs will achieve these objectives or potential future reductions in injuries and fatalities. As this is a forward-looking assessment, the ultimate impact has not yet occurred, and there are many sources of uncertainty associated with our estimates of total benefit. Usage rates of new restraint designs, the speed with which new designs are purchased, changes to trends in the frequency with which ambulances are used, and a host of other factors will all affect the ultimate value of NIOSH's research on this subject. Despite this uncertainty, the three estimates we provide suggest there is potential for this NIOSH research to provide significant safety benefits to future ambulance occupants.

4. Improved Amputation Surveillance

Introduction

NIOSH has provided funding to the state of Michigan to conduct occupational injury and illness surveillance since 1988. Three groups in Michigan have worked together on work-related surveillance: the Division of Occupational and Environmental Medicine at Michigan State University (MSU), the Michigan Occupational Safety and Health Administration (MIOSHA), and the Michigan Department of Health and Human Services (MDHHS). As part of this funding, Michigan developed ways to better track work-related injuries, including amputations.[66] The goal of the NIOSH-funded program was to both better understand the extent of underreporting of work-related amputations and to obtain information to promote worker safety.

In this case study we first summarize the literature on undercounting of work-related amputations and the burden of amputation injuries. We then describe the NIOSH-funded amputation surveillance program in Michigan and how the results from the program were used by MIOSHA, as well as how the program influenced similar efforts in Massachusetts. Next, we seek to quantify some of the outcomes of the program using data on worksite inspections. Finally, we note interesting areas for future research and then conclude.

Undercounting of Work-Related Amputations

Data on the number of amputations through time and by state are available from the BLS Injuries, Illnesses, and Fatalities (IIF) program, Survey of Occupational Injuries and Illnesses (SOII) (see Figure 4.1).[67] However, work sponsored by NIOSH and others has documented severe undercounts of work-related illnesses and injuries in the BLS. This undercounting has been reconfirmed by many researchers, and includes acute, obvious injuries such as amputations.[68]

[66] Over 90 percent of amputations in Michigan in recent years are finger or partial finger amputations, although amputations may involve other extremities including hands, arms, toes, feet, or legs.

[67] The classification system for amputations changed between 2010 and 2011, and data may not be comparable between the classification systems. We obtained our data from BLS, undated-c, for 2000–2002; BLS, undated-a, for 2003–2010; and BLS, undated-b, for 2011–2018.

[68] Undercounting in the BLS SOII has been extensively documented. For a list of BLS-sponsored and some other research on undercounting (including a report specifically about amputations in Massachusetts), see BLS, 2019c. See also the special issue of the *American Journal of Industrial Medicine*, Vol. 57, No. 10, whose editors conclude that "the overall conclusion, across the three jurisdictions [CA, MA, WA] and across methodologies, is that the SOII significantly undercounts—and therefore underestimates—the number of injuries, even when looking only at objectively verifiable and often serious injuries such as amputations" (Spieler and Wagner, 2014, p. 1077). Other studies exploring the importance of measurement methods in this area include Tak et al., 2014.

The initial work on amputation surveillance in Michigan was performed by Stanbury, Reilly, and Rosenman (2003).[69] The researchers identified 693 work-related amputations in Michigan compared with 440 in the BLS data. Subsequent to this publication, injury reporting regulations were promulgated by MDHHS to formalize the amputation surveillance program. Seven years of data from the NIOSH-funded program in Michigan were summarized by Largo and Rosenman (2015), and data on this program through 2016 are publicly available from MSU (undated-a). Using emergency department records, hospital records, and worker compensation data, the authors document 4,140 work-related amputations in Michigan from 2006 to 2012. This compares to 1,770 work-related amputations reported in the BLS SOII (43 percent of the total identified by the surveillance program). The authors further report that men were six times more likely to suffer work-related amputations than women and that the Wood Product Manufacturing and Paper Manufacturing industries had the highest rates of work-related amputations. From 2013 to 2016, the Michigan surveillance system identified 1,964 work-related amputations in Michigan compared with 850 (43 percent of the true number) in the BLS data.

Without accurate information on the number, types, and causes of work-related amputations, public health officials, MIOSHA, and other policymakers cannot optimally target resources to prevent injuries. For example, state governments may decide to allocate additional resources to preventing work-related amputations if they realize the extent of the problem. Further, it is difficult to measure progress on reducing work-related amputations if accurate, stable estimates of the current number do not exist (Rosenman, 2013).

The Burden of Work-Related Amputations

Most work-related amputations in the Michigan surveillance data involve whole or partial finger amputations (MSU, undated-a). Finger amputations as a percentage of amputations in the data did not vary much from year to year, with a minimum of 94.1 percent in 2012 to a maximum of 96.3 percent in 2014. Approximately 12.7 percent of the amputations recorded in medical records involved multiple fingers. The distal phalanges of the index and middle fingers were the most frequently amputated areas.[70]

Medical and worker compensation costs for work-related amputations in Michigan are not available. However, previous studies provide some estimates of the costs of work-related amputations. McCall and Horwitz (2006) studied the workers' compensation claims for work-related amputations in Kentucky from 1994 to 2003. Similar to the Michigan data, amputations

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[69] See also Rosenman et al., 2006.

[70] No MSU amputation report exists for 2010. Data on the details of finger amputations are only found in the hospital and emergency department medical records, which provide more detail on finger injuries than workers' compensation claims data.

of fingers accounted for most of the amputations (92.6 percent) in the Kentucky data. The authors find that the average total indemnity payment[71] per work-related amputation claim was $8,822 (median = $2,054, minimum = $0, and maximum = $401,125).[72] For amputations involving nonthumb fingers, the average workers' compensation claim was $5,758 (median = $2,113) and for thumbs the average was $6,752 (median = $1,292) (McCall and Horwitz, 2006).

A more recent estimate from the National Council on Compensation Insurance's Workers Compensation Statistical Plan database puts the costs of amputations for workers who filed a compensation claim in 2015 or 2016 at an average of $28,304 for indemnity costs and $66,900 for medical costs (Injury Facts, undated). Unfortunately, these data are not broken out into part of the body that was amputated, and it is not clear exactly which states the data cited come from.

Overview of NIOSH's Activities Regarding Amputations in Michigan

Beginning in 2004, NIOSH funding was used to develop a multisource surveillance system to improve the understanding of the magnitude of work-related amputations in Michigan and ultimately to improve the targeting of worksite inspections. Unsafe worksite conditions can create undo risk of injuries that result in amputations, and Michigan was interested in promoting a better understanding of amputations and promoting efforts that would increase worker safety and lead to their reduction. The program would not exist without funding from NIOSH as the program does not receive any other outside funding.[73] The surveillance program specifically began reviewing medical records for patients treated for amputations and referring cases meeting designated criteria to MIOSHA. Beginning with data received in 2006, a surveillance system to track all work-related amputations treated at Michigan hospitals was established. The surveillance system for amputation is part of a larger work-related injury surveillance system also funded by NIOSH that includes burns, crushing injuries, and skull fractures. The emergency department and hospital data on work-related amputations were combined with data from the Michigan Workers' Compensation Agency to help the researchers develop a new system to monitor hazardous working conditions, specifically conditions that might lead to amputations.[74] From 2006 to 2012, worksites of emergency and hospital-treated cases that met the following additional criteria were

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[71] With workers' compensation, payments made to an injured or sick employee as a result of injury or illness occurred due to employment are called indemnity costs.

[72] Note that this estimate may be high since only indemnification costs for amputations that took a week or more of recovery time were recorded since Kentucky provides workers' compensation only for claims of seven or more days of lost work time.

[73] Interview with Dr. Kenneth Rosenman conducted via phone January 28, 2019. Amputations were the first nonfatal injury that the program focused on but there are currently five other types of injuries that are being tracked.

[74] See MSU, undated-a, specifically "Work-Related Amputations in Michigan, 2006." Although the program began in 2004, we have ten observations in the data from 2003, and it appears that either some elements of the program were in place during that year or that data from that year were examined in 2004.

referred to MIOSHA if (a) the worksite was located in Michigan; and either (b) the company was in an industry MIOSHA had identified as having high injury rates, or (c) the amputation was caused by a mechanical power press. After 2012, the industry priority requirement was dropped, and the requirements became "a) the worksite was located in Michigan; and b) the amputation potentially was caused by a mechanical power press or another hazard likely to be found upon inspection" (MSU, undated-a). Note that cases that were identified solely through workers' compensation records were not referred to MIOSHA because data provided by the Michigan Workers' Compensation Agency can only be used for research and not for enforcement purposes.[75] As noted, Largo and Rosenman (2015) counted 4,140 amputations in the state compared with 1,770 cases counted by the BLS.[76] The authors report that as a direct result of the new system during this time period 173 safety inspections were conducted. These inspections resulted in 1,566 violations cited and $652,755 in penalties assessed.[77]

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[75] See MSU, undated-a, for the yearly reports for the amputation surveillance program. From 2006 to September 2008, the industries were based on Standard Industrial Classification (SIC) Major Group Code and included: 20 Manufacturing—Food and Kindred Products; 24 Manufacturing—Lumber and Wood Products, Except Furniture; 25 Manufacturing—Furniture and Fixtures; 30 Manufacturing—Rubber and Miscellaneous Plastics Products; 33 Manufacturing—Primary Metal Industries; 34 Manufacturing—Fabricated Metal Products, Except Machinery and Transportation Equipment; 35 Manufacturing—Industrial and Commercial Machinery and Computer Equipment; 37 Manufacturing—Transportation Equipment. After September 2008, they were based on NAICS Code and included: 312 Beverage and Tobacco Product Manufacturing; 321 Wood Product Manufacturing; 326 Plastics and Rubber Products Manufacturing; 327 Nonmetallic Mineral Product Manufacturing; 331 Primary Metal Manufacturing; 332 Fabricated Metal Product Manufacturing; 333 Machinery Manufacturing; 336 Transportation Equipment Manufacturing; 423930 Recyclable Material Merchant Wholesalers; 561730 Landscaping Services. These industries were included to support MIOSHA in addressing Objective 1.1 of their 2009–2013 Strategic Plan: "Reduce by 20% the rate of worker injuries and illnesses in high-hazard industries (defined as those in the following NAICS subsectors: 312, 321, 326, 327, 331, 332, 333, 336, 423930, 561730, 622, 623)." Two additional industries are included in the strategic plan that were not included in the surveillance program: 622 Hospitals; 623 Nursing and Residential Care Facilities. This objective was changed in the 2014–2018 Strategic Plan, where Objective 1.1 reads: "Reduce by 15% the rate of worker injuries and illnesses in high-hazard industries (defined as those in the following NAICS subsectors: 312, 331, 332, 333, 336, 488, 493, 622, 623, 721)." Besides those already noted, this includes 488 Support Activities for Transportation; 493 Warehousing and Storage; 721 Accommodation.

[76] Undercounting of amputations in Michigan by the BLS SOII appears to have gotten slightly worse over time. Stanbury, Reilly, and Rosenman, 2003, report that in 1997 estimates released by BLS were only 64 percent of the true number of amputations for that year in Michigan. In 2016 the system found 431 work-related amputations among Michigan residents, while the BLS estimate was 240 or 56 percent of the true number. See also MSU, undated-a, specifically "Work-Related Amputations in Michigan, 2016."

[77] The original article provides many more details on the specifics of the program and data sources. See also MSU, undated-a, for the yearly reports of the program for 2006–2009 and 2011–2015. Note that the data used in this study, although obtained from Largo and Rosenman, 2015, differ slightly from their study. For example, between 2006 and 2012, our data record 233 inspections based on referrals with total initial violations of 1,971 and total initial penalties of $804,840. It is not clear why these differences exist but some of the discrepancy in yearly numbers may be driven by differences in year labeling. Largo and Rosenman seem to have based their analysis on the year that the amputation happened while we base our analysis on the year that the inspection took place. Because of the time between amputation and referral and referral and inspection, significant time may have passed between amputation and inspection, causing the mismatch in data. We do not have the date of the original amputation in our data but for

Benefits of the NIOSH-Funded Surveillance Program in Michigan

The NIOSH-funded surveillance program in Michigan was successful in its goals of producing additional information on the extent and characteristics of amputations in Michigan and in working with MIOSHA to target better enforcement of safety standards. It had the additional benefit of being a model for tracking other injury types and providing an example that other states could follow in their own surveillance activities.

Better Information About Amputations in Michigan

As noted, the amputation surveillance program provided valuable information in the form of an estimate of the actual number of amputations in Michigan, which was much higher than the estimates provided by BLS. The program also helped to characterize workers and industries with high amputation rates. From Largo and Rosenman (2015), we learn that:

- Men comprised 88 percent of workers who sustained an amputation.
- Among men, the highest rates were for those in their 20s; among women, those aged 16–19 had the highest rates.
- The industries with the highest work-related amputation rates were Wood Product Manufacturing and Paper Manufacturing.
- Power saws and presses were the leading causes of injury.
- Michigan's multisource system and workers' compensation claims showed a decrease in the amputation rate from 2006 to 2009 and then a relatively stable rate from 2010 to 2012.

These and other important details about work-related amputations in Michigan, which are contained in the yearly reports published as part of the surveillance program (MSU, undated-a) and in hazard alerts published by MSU (undated-b), can help to inform employee and employer education outreach efforts as well as future regulations and recommendations to promote worker safety. Additionally, information on race can be used to address health disparities in injury rates. This is not possible with BLS data alone as BLS does not collect information on race.

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instances where we have both referral date and inspection date, inspection date was on average 83 days after referral (median: 42; min.: 1; max.: 560). This was 107 in 2003–2009 and 42 in 2011–2018, showing that the process is becoming more efficient over time. A shorter time between amputation and inspection in recent years provided an opportunity for quicker remediation.

Better Targeting of Inspections

The Occupational Safety and Health Act of 1970 regulates conditions in private-sector establishments, and OSHA, which was created by the act, is charged with ensuring the "safe and healthful working conditions for working men and women by setting and enforcing standards and by providing training, outreach, education and assistance" (OSHA, undated-a). OSHA inspects worksites in the United States to monitor compliance with laws and regulations and to make sure working conditions are safe for workers. Twenty-two states/territories, including Michigan (MIOSHA), operate their OSHA under state plans, which are approved by federal OSHA. Six additional states/territories have state plans that cover state and local government workers, but private workers are covered by federal OSHA.[78] It has been estimated that there is only about one OSHA compliance officer for every 59,000 workers in the United States (OSHA, undated-b). MIOSHA has about 55 health and safety inspectors to cover the nearly 200,000 establishments and 3.7 million workers in the state; or about one MIOSHA officer for every 67,724 workers. Performing a total of about 5,000 inspections a year, inspectors are only able to inspect between 2 and 3 percent of worksites in a given year.[79] As a former MIOSHA inspector told us, "The real issue . . . is that you can only do so many inspections. The challenge is to try to identify where inspections will have the most impact."[80]

Much of modern economics is concerned with how to allocate scarce resources to maximize benefits or minimize costs. Given the number of compliance officers per worker, the allocation of resources is an especially important problem for OSHA (and many other government agencies). It is often difficult to get voters and state and federal legislatures to allocate additional resources for oversight agencies such as OSHA. Consequently, decisionmakers within these agencies must often search for ways to maximize the protection of workers in the most efficient manner possible given the limited resources available.[81]

The amputation surveillance program in Michigan helped to identify hazardous worksites that may have not otherwise been detected and promoted remediation efforts at these worksites. Unlike data from BLS, the multisource system could be used by MIOSHA for enforcement. Because the names of employers in the BLS survey are confidential, MIOSHA can use the

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[78] For more information, see OSHA, undated-c, undated-d.

[79] BLS, 2019a; United States Census Bureau, undated; Dixon, 2019; interview with David Michaels, former assistant secretary of labor for occupational safety and health, conducted via phone March 28, 2019; interview with Adrian Rocskay of the General Industry Safety and Health Division of MIOSHA, conducted via phone April 29, 2019. See also Berkowitz, 2018.

[80] Interview with Doug Kalinowski conducted via phone on June 6, 2019.

[81] Note that inspectors can often positively affect work environments even without conducting formal inspections through phone calls, consultation programs, and other communications with employers. However, in person inspections are believed to have greater impact in many cases and are more thorough (Michaels interview). For a recent analysis of consultation programs see, OSHA, 2018.

information only to identify trends and high-risk industrial sectors; it cannot use the BLS information to conduct an inspection at the facility where the amputation occurred. Emergency department and hospital records from the multisource system allowed for direct targeting of worksites.

A Model for Other Surveillance Activities

While this case study focuses on Michigan, it should be noted that NIOSH funds similar programs in other states, including Massachusetts and Illinois.[82] The design of the program in Massachusetts was directly informed by the amputation work in Michigan. The Occupational Health Surveillance Program was started in 2011 by the Massachusetts Department of Public Health (MDPH). Similar to the program in Michigan, the Massachusetts program used Massachusetts workers' compensation claims to identify worksites where amputations had occurred and then passed on this information to OSHA.[83] Between 2011 and the first part of 2019 the program made 434 referrals to OSHA and another 28 to the Massachusetts Department of Labor Standards (DLS). OSHA conducted more than 280 inspections of worksites to investigate amputations, based solely on referrals from the MDPH Occupational Health Surveillance Program. DLS conducted an additional 28 inspections of public sector worksites (state, city, and town facilities) based solely on referrals from MDPH.[84] Individuals within the Michigan and Massachusetts programs routinely attend conferences, write papers, and present workshops to disseminate the knowledge they have gained and help other states to replicate their successful efforts. The two departments have also collaborated together to produce publicly available documents to provide guidance to other public health departments.[85]

Information about the effectiveness of the Massachusetts surveillance program was included in public comments in support of federal regulation 29 CFR 1904.39 in 2015. This regulation mandated that employers report work-related in-patient hospitalization of one or more employees, amputations, and losses of an eye as a result of work-related incidents to OSHA. OSHA explained that "[a]mputations include some of the most serious types of injuries and tend to result in a greater number of lost workdays than most other injuries . . . Furthermore,

[82] NIOSH supports 26 states to do some kind of state-based surveillance program (Rosenman interview). See also Davis et al., 2014, and Friedman et al., 2013.

[83] Although the Massachusetts program has used hospital records for research purposes, they do not currently have the resources to include hospital records as part of their ongoing amputation surveillance efforts according to an interview with Elise Pechter, Emily Sparer-Fine, Kathleen Grattan, and Michael Fiore conducted via phone on April 25, 2019.

[84] Information based on Pechter et al. interview. Data on the number of amputations identified in the workers compensation files were only available for 2014–2019. Approximately 615 amputations were identified during that time period.

[85] Pechter et al. interview. See, for example, Council of State and Territorial Epidemiologists, Occupational Health Surveillance Subcommittee, 2011.

amputations differ from other types of serious injuries because they have long-term or permanent consequences (OSHA, 2014)."[86] Comments submitted about the Massachusetts surveillance program and its research regarding amputations and reporting were cited as general support for the regulation, as evidence that the in-patient hospitalization rule alone would not sufficiently capture many amputations, and as an example that surveillance programs could provide data to OSHA for enforcement purposes.[87] No comments about the Michigan surveillance program were made in response to the proposed rule, but the findings in Michigan paralleled those in Massachusetts about the importance of better reporting of amputations and the utility of surveillance in better enforcement.

If all employers perfectly complied with the new regulations and reported all amputations directly to OSHA starting in 2015, a surveillance program for amputations like the ones in Michigan and Massachusetts would no longer be necessary. However, in Michigan, only approximately 30 percent of amputations reported by hospitals were also reported by employers to the MIOSHA severe injury reporting database.[88] Paradoxically, uneven reporting may actually make a surveillance program more useful as it can be difficult to distinguish industries and worksites that have more amputations from those that are more likely to report; high reported amputation rates could reveal that the industry is very dangerous, or it could indicate that the industry or employer is more compliant with the regulation than other employers or industries. Disentangling actual amputation rates from reported rates remains important as long as many employers do not report.[89]

It should also be noted that the program in Michigan, as well as NIOSH-funded programs in other states, now routinely tracks many different worksite injuries in addition to amputations, passing on valuable information to MIOSHA.[90]

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[86] See also Michaels, 2016. Although the Michigan surveillance program is not mentioned in the documentation to the new rule, influence of the Michigan and Massachusetts programs on the federal regulation was noted by Dr. David Michaels in his interview with the authors. Note that after 2015, as employers came into compliance with regulations, the numbers of amputations found by MDPH alone that resulted in inspections dropped, as more employers reported these injuries themselves. The Massachusetts and Michigan surveillance programs were also cited in National Academies of Sciences, Engineering, and Medicine, 2018.

[87] See, OSHA, 2014, for the documentation for the standard.

[88] According to data provided by Kenneth Rosenman, 126 of the 427 reports of amputations from hospitals in 2018 were also reported by employers to the MIOSHA severe injury reporting database. In 2017, this proportion was 122 out of 391, and in 2016 this proportion was 110 out of 390.

[89] Michaels interview.

[90] See NIOSH, 2018a, for more on state surveillance programs across the nation sponsored by NIOSH.

Quantifying the Effects of the NIOSH-Funded Surveillance Program in Michigan

The other case studies in this report used a five-step process for estimating the economic benefits of the studied program. We can only credibly complete the first three steps in this case study.

Step 1: Identify the Target Population

Many workers are in danger of work-related injuries, including amputations. Risk of such injuries is highest for those who work in agriculture, construction, manufacturing, wholesale trade, and accommodations and food service. Almost 40 million people across the United States work in these industries, including nearly 1.4 million Michiganders.[91]

Step 2: Estimate the Number of Affected Individuals

There were 4,140 work-related amputations in Michigan between 2006 and 2012. This was more than twice as many as reported by the BLS SOII. Eighty-eight percent of those who suffered a work-related amputation were men, with the greatest number coming from Wood Product Manufacturing and Paper Manufacturing industries (Largo and Rosenman, 2015).

Step 3: Estimate the Reduction in Risk

It is not clear how to measure the reduction in risk of amputations due to the Michigan surveillance program. We know that the program changed the mix of MIOSHA inspections by referring employers who had an amputation at their workplace to MIOSHA. As detailed in Table 4.1, about 40 percent of these workplaces were then inspected by MIOSHA. As explored below, these inspections resulted in more violations found and penalties assessed than the typical MIOSHA inspection.

However, we do not have a credible way to translate these more effective inspections into a reduction in amputation rates. Despite the undercounting, BLS data are often correlated with the more comprehensive data used by researchers. In the BLS data we see the number and rates of amputations decrease through time both in Michigan and in the rest of the United States. Amputations decreased substantially in Michigan from the 2003–2006 period (average 390/year) to the 2008–2017 period (average 191/year) (see Figure 4.1). This is a 51-percent decrease. However, while amputations do seem to decrease more in Michigan than in other areas, this difference is likely driven by the changing industrial mix and largely goes away when we control for industry. While it is likely that the surveillance program helped to decrease the number of

[91] BLS, 2018, 2019b.

Table 4.1. Worksites Referred by the Michigan Surveillance Program and Inspections Conducted by MIOSHA, 2006–2016

Year	Worksites Referred	Inspections Conducted	Percent
2006	132	41	31.06%
2007	140	68	48.57%
2008	111	35	31.53%
2009	58	5	8.62%
2010	–	–	–
2011	37	18	48.65%
2012	17	13	76.47%
2013	43	20	46.51%
2014	46	28	60.87%
2015	22	7	31.82%
2016	14	10	71.43%
Total	620	245	39.52%
Average per year	62	25	39.52%

SOURCE: MSU, undated-a.
NOTE: No report is available for 2010.

amputations in Michigan, it is unlikely that we could precisely measure this impact given the size of the program (an average of about 24 inspections resulting from referrals per year out of over 5,300 total inspections among 200,000 establishments).

Step 4: Estimate the Number of Avoided Injuries and Fatalities

Because we cannot translate more effective inspections into reductions in the risk of amputations, we cannot credibly complete Step 4.

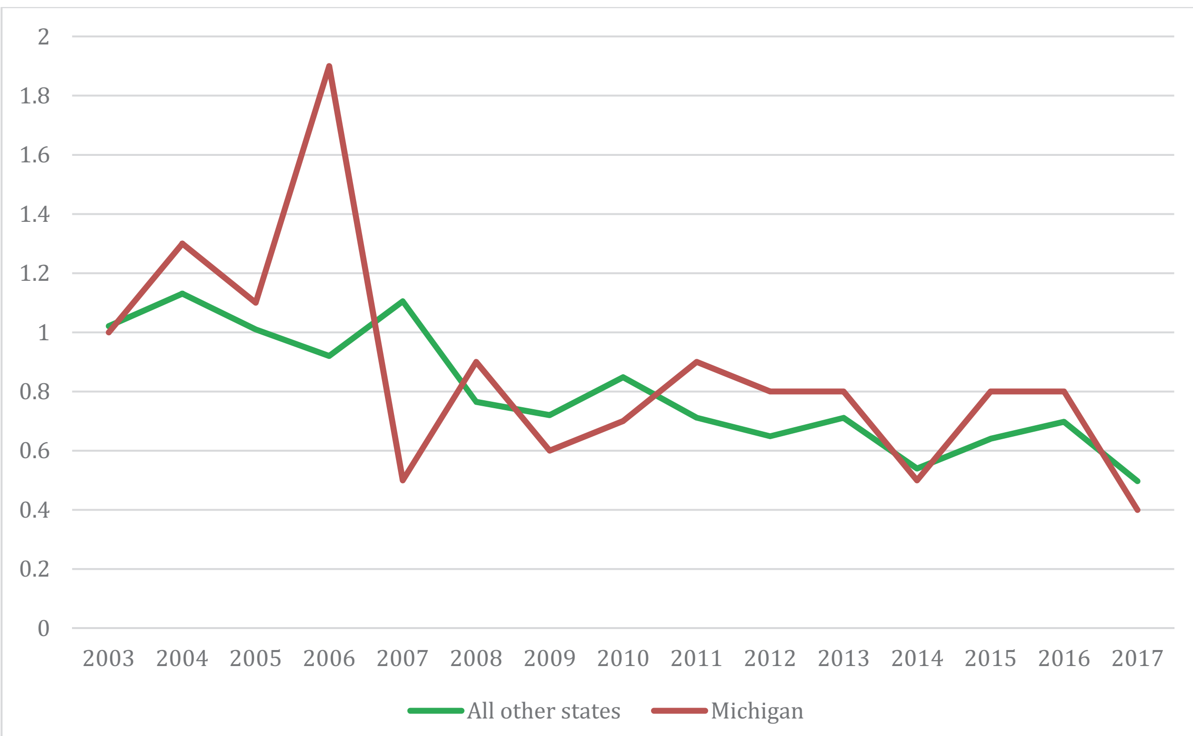
Step 5: Monetize Avoided Injuries and Fatalities

Because we cannot translate more effective inspections into reductions in the risk of amputations, we cannot credibly complete Step 5.

What we can do is examine the proximate outcomes of the Michigan surveillance program: the MIOSHA inspections that resulted from the program. According to MIOSHA officials, many of these inspections would not have happened but for the surveillance program. However, MIOSHA did not gain any additional resources from the program, so it is most accurate to think of the program as changing the mix of inspections—inspections referred by the surveillance program likely took the place of other inspections. Below we compare the inspections from the surveillance program to the typical inspection in Michigan over this time period, controlling for type, whether it was complete or partial (scope), year, and industry. While we do our best to control for differences, the analyses are descriptive and should not be considered to reveal the causal effect of the program. While we see that the surveillance program led to inspections that found more violations and assessed higher penalties than other inspections, we do not know how agency resources would have been allocated in the absence of the program. Since we do not know what inspections would have been done if the surveillance program did not exist (i.e., we do not know the counterfactual), we cannot claim that the program caused inspections to find more violations and penalties than they otherwise would have. However, we find that the surveillance inspections found more violations and assessed higher dollar amounts of penalties than similar nonsurveillance inspections. We discuss these results and their limitations below.

We do not have metrics to quantify the benefits of information on the extent of undercounting and the characteristics of amputations that were provided by the Michigan amputation surveillance program. We also do not have a way to measure the impact of the Michigan amputation surveillance program on promoting surveillance of other injuries in Michigan or promoting similar activities by other state programs or federal OSHA. The amputation program did lead to similar surveillance systems for other types of injuries, including burns, crushing injuries, skull fractures, and farm injuries (see Kica and Rosenman, 2012, 2014, 2018, 2019). To the extent that these programs have expanded beyond amputations and beyond Michigan, this case study will underestimate the true effects of the program and should be considered only illustrative.

Figure 4.1. Amputation Rate per Year in Michigan and All Other States as Reported by BLS, 2003–2017



SOURCE: BLS data.
NOTES: Rate of amputations per 10,000 full-time workers were calculated by BLS as: (N / EH) × 20,000,000, where N = number of injuries and illnesses, EH = total hours worked by all employees during the calendar year, and 20,000,000 = base for 10,000 full-time equivalent workers working 40 hours per week, 50 weeks per year). "All other states" includes the 45 other states in the data.

In sum, given data limitations, we are not able to assign an exact, specific dollar amount to the benefits provided nor to trace the proximate outcomes that we observe (violations and penalties) through to a precise reduction in amputations and increased worker safety. Much work remains to be done to tie better targeting of OSHA resources to the outcomes that we care most about: reduced worksite injuries and increased human well-being.

Data on OSHA Inspections

We downloaded data on all MIOSHA inspections in Michigan for the years 2003–2018 from the online OSHA (2019) database. The database contains information on all inspections, both for states that operate under their own state plans as well as those that operate under federal OSHA. The online database contains information on the date the inspection was initiated; a unique (within-state) inspection number; the name and address of the employer inspected, the North American Industry Classification System (NAICS) industry that the employer belongs to (six digits); the type and scope of the inspection; whether the employer is privately owned; information on related activities; whether it was an inspection for health or for safety; count of serious, willful, repeat, other, and total violations and penalties distinguished between initial and current violations and initial and current penalties; failure-to-abate (FTA) amount; and often some details about the nature and outcome of the violations. The Michigan data represent 1,057 different NAICS codes, and the surveillance program data represent 139 different NAICS codes. An example of the information provided for an inspection on the website can be seen in Figure 4.2.

Figure 4.2. Example of Inspection Data as Reported on OSHA Website

Inspection Detail

Case Status: CLOSED

Inspection: 1012118.015 - Wolverine Metal Stamping

Inspection Information - Office: Michigan Safety Gen

Nr: 1012118.015 Report ID: 0552652 Open Date: 01/13/2015

Wolverine Metal Stamping
3600 Tennis Court St
Saint Joseph, MI 49085
SIC:
NAICS: 332119
Mailing: 3600 Tennis Court St, Saint Joseph, MI 49085

Union Status: NonUnion

Inspection Type:	Referral		
Scope:	Partial	Advanced Notice:	N
Ownership:	Private		
Safety/Health:	Safety	Close Conference:	02/13/2015
Emphasis:	S:Enf Targeted	Close Case:	05/27/2015

Related Activity:	Type	ID	Safety	Health
	Referral	925574	Yes	

Case Status: CLOSED

Violation Summary

	Serious	Willful	Repeat	Other	Unclass	Total
Initial Violations	1					1
Current Violations	1					1
Initial Penalty	$3,000	$0	$0	$0	$0	$3,000
Current Penalty	$1,500	$0	$0	$0	$0	$1,500
FTA Amount	$0	$0	$0	$0	$0	$0

Violation Items

#	ID	Type	Standard	Issuance	Abate	Curr$	Init$	Fta$	Contest	LastEvent
1.	01001A	Serious	19100147 C04 I	03/24/2015	04/26/2015	$1,500	$3,000	$0		I - Informal Settlement
2.	01001B	Serious	19100147 C07 I A	03/24/2015	04/26/2015	$0	$0	$0		I - Informal Settlement

SOURCE: OSHA, 2015.

The data contain 86,136 inspections for Michigan during our time frame. The number of total inspections and the number of inspections identified by the Michigan surveillance program by year can be found in Table 4.2.

Table 4.2. Total Number of Inspections in Michigan Identified in the OSHA Data

Year	Other Inspections	Mich. Surveillance Inspections	Total
2003	5,247	10	5,257
2004	5,955	20	5,975
2005	4,875	16	4,891
2006	5,718	35	5,753
2007	5,919	43	5,962
2008	5,417	58	5,475
2009	5,591	52	5,643
2010	6,010	19	6,029
2011	5,828	11	5,839
2012	5,884	15	5,899
2013	5,416	19	5,435
2014	5,099	27	5,126
2015	4,582	16	4,598
2016	4,699	12	4,711
2017	4,974	11	4,985
2018	4,531	27	4,560
Total	85,745	391	86,136

SOURCE: Author analysis based on data from OSHA, 2019.

Inspection type includes two main categories: programmed and unprogrammed. Programmed inspections are scheduled because of selection criteria chosen by OSHA according to national, local, or regional priorities. "Program-related inspections" are inspections of employers at multi-employer worksites whose activities were not included in the initial programmed inspection.[92] Unprogrammed inspections respond to information about hazardous working conditions such as imminent dangers, fatalities/catastrophes, complaints, and referrals. This category also includes follow-up and monitoring inspections. "Unprogrammed-related inspections" are inspections of employers at multi-employer worksites whose operations are not directly addressed by the subject of the conditions identified in the unprogrammed inspection.[93] In the data, type of inspection takes on the values of injury, complaint, fatality/catastrophe, follow-up, monitoring, planned/programmed, program-related, program other, referral, unprogrammed-related,

[92] Multi-employer worksites are worksites where many employers have permanent or temporary operations and may be working together on a specific project such as the construction of a large building.

[93] See OSHA, 2016, for more on the different types of inspections and their meaning.

unprogrammed other, variance, and other. Note that in the data inspections are referred to as "planned" while in the manual they are called "programmed."[94] Planned inspections make up 73 percent of the observations in the Michigan data, followed by complaint at 14 percent, referral at 4 percent, program-related at just under 3 percent, and unprogrammed-related at 2 percent. While we initially believed that all referrals from the Michigan surveillance program would be classified in the data as "referrals," this is not the case. Of the 391 inspections done due to the surveillance program that we have in the data, 64 percent (249) are categorized as "planned," 29 percent (115) are categorized as "referral," 3 percent (12) are categorized as "program-related," 2 percent (8) are categorized as "complaint," 1 percent (5) are categorized as "accident,"[95] and 1 each are categorized as "program other" and "follow-up." The reasons why referrals from the Michigan surveillance program were classified into different inspection types by MIOSHA is unknown.

Inspections are also categorized into "Safety" inspections and "Health" inspections depending on the general reason for the inspection. In the full sample, 82 percent of observations are coded as "Safety" inspections. Only four of the 391 observations from the Michigan surveillance program are coded as "Health" inspections, with 99 percent coded as "Safety."

Another important variable records the scope of the inspection performed. A "comprehensive" inspection is a "substantially complete inspection of the potentially high hazard areas of the establishment," whereas in a "partial" inspection the "focus is limited to certain potentially hazardous areas, operations, conditions or practices at the establishment." In general, comprehensive inspections are wall-to-wall investigations of a worksite while partial inspections focus on the area of the complaint, imminent danger, or referral. Partial inspections can be expanded if the inspector sees something that merits investigation in the course of the inspection even if it is not related to the original reason for the inspection. The scope variable also records when an inspection did not take place and the reason for it (business closed, fewer than ten employees, entry refused, etc.). While on average comprehensive inspections take longer than partial inspections, this is often not the case and can vary widely by inspection type and across industries. However, we do not have a measure of the amount of time that a given inspection took. For the entire Michigan dataset, 52 percent of the observations in the database were complete inspections and 39 percent were partial. In the remaining 9 percent of observations an inspection did not happen for various reasons. Observations in the data resulting from information provided by the Michigan surveillance program were similar, with 51 percent being complete inspections and 44 percent partial inspections.

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[94] The reason for the difference in terminology is not clear.

[95] Although we have generally used the word "injury" to describe the event that results in an amputation, the OSHA data use the word "accident."

For outcomes, we focus on total initial violations and total initial penalties. Initial violations and penalties represent those initially assessed when the citation was first issued to the employer, whereas current violations and penalties represent the amounts after any settlements or judicial actions that may have resulted in reductions. Results are similar if we focus on “serious initial violations,” “serious current violations,” or “total current violations” instead of “total initial violations,” and on “serious initial penalties,” “serious current penalties,” or “total current penalties” instead of “total initial penalties.” Total current violations and total current penalties may represent the outcomes of complicated bargaining interactions and may be influenced by employer resources and other considerations not directly related to worker safety. For this reason, we prefer total initial violations and total initial penalties. Descriptive statistics for all potential outcome variables for both the surveillance and nonsurveillance program observations can be found in Table 4.3. Table 4.4 shows the mean and median for total initial violations and penalties as well as total current violations and penalties broken out by whether the inspection was from the Michigan surveillance program or not and also by type of inspection as classified by MIOSHA. The data in the tables anticipates our findings. Without any controls for other variables, the median and mean are often higher for surveillance inspections than other inspections. For example, the mean (median) total initial violations for surveillance inspections is 6.98 (3) compared with 2.50 (1) for other inspections. These patterns will continue to hold as we control for other variables. Figure 4.3 shows the distribution of total initial violations for surveillance program referrals and all other inspections in Michigan for observations with values that are greater than zero and less than 30. While both groups have many observations with low violation counts, observations from the surveillance program appear to have greater violation counts.

Table 4.3. Descriptive Statistics for Potential Outcome Variables (Numbers of Violations and Dollars of Penalty)

	Other Inspections					Mich. Surveillance Inspections				
Variable	Min.	Median	Mean	Max.	St. Dev.	Min.	Median	Mean	Max.	St. Dev.
Serious Initial Violations	0	0	1.11	102	1.97	0	1	3.25	28	4.16
Willful Initial Violations	0	0	0.00	8	0.11	0	0	0.02	4	0.23
Repeat Initial Violations	0	0	0.08	39	0.54	0	0	0.16	12	0.92
Other Initial Violations	0	0	1.31	44	2.42	0	1	3.55	42	5.20
Unclass Initial Violations	0	0	0.00	3	0.01	0	0	0.00	0	0.00
Total Initial Violations	0	1	2.50	154	4.01	0	3	6.98	70	8.89
Serious Current Violations	0	0	1.06	104	1.93	0	1	3.17	28	3.99
Willful Current Violations	0	0	0.00	8	0.08	0	0	0.00	0	0.00
Repeat Current Violations	0	0	0.07	39	0.53	0	0	0.15	9	0.80
Other Current Violations	0	0	1.33	44	2.43	0	1	3.49	42	5.09
Unclass Current Violations	0	0	0.00	5	0.03	0	0	0.00	0	0.00
Total Current Violations	0	1	2.47	150	3.98	0	3	6.81	70	8.57
Serious Initial Penalty	0	0	971.04	442,150	3,075.81	0	1,800	3,169.50	52,000	4,887.22
Willful Initial Penalty	0	0	129.50	429,000	4,194.43	0	0	268.54	70,000	3,953.84
Repeat Initial Penalty	0	0	231.93	403,200	3,130.26	0	0	793.56	110,360	6,315.02
Other Initial Penalty	0	0	25.84	10,163	197.16	0	0	177.43	5,000	774.84
Unclass Initial Penalty	0	0	0.55	35,000	124.60	0	0	0.00	0	0.00
Total Initial Penalty	0	0	1,358.86	731,790	6,901.08	0	2,100	4,409.03	134,310	10,122.25
Serious Current Penalty	0	0	547.79	184,160	1,749.94	0	900	1,629.17	21,150	2,372.93
Willful Current Penalty	0	0	53.61	280,000	2,228.84	0	0	0.00	0	0.00
Repeat Current Penalty	0	0	119.29	403,200	1,999.27	0	0	368.58	40,080	2,527.94
Other Current Penalty	0	0	25.51	25,000	201.19	0	0	98.09	4,500	440.91
Unclass Current Penalty	0	0	6.67	119,720	681.78	0	0	0.00	0	0.00
Total Current Penalty	0	0	755.48	431,100	4,083.52	0	1,020	2,095.85	53,460	3,918.85
Total FTA Amount	0	0	16.96	132,000	877.44	0	0	27.33	10,687	540.46
Serious Initial Violations	0	0	1.11	102	1.97	0	1	3.25	28	4.16
Willful Initial Violations	0	0	0.00	8	0.11	0	0	0.02	4	0.23
Repeat Initial Violations	0	0	0.08	39	0.54	0	0	0.16	12	0.92
Other Initial Violations	0	0	1.31	44	2.42	0	1	3.55	42	5.20
Unclass Initial Violations	0	0	0.00	3	0.01	0	0	0.00	0	0.00
Total Initial Violations	0	1	2.50	154	4.01	0	3	6.98	70	8.89
Serious Current Violations	0	0	1.06	104	1.93	0	1	3.17	28	3.99
Willful Current Violations	0	0	0.00	8	0.08	0	0	0.00	0	0.00
Repeat Current Violations	0	0	0.07	39	0.53	0	0	0.15	9	0.80

Variable	Other Inspections					Mich. Surveillance Inspections				
	Min.	Median	Mean	Max.	St. Dev.	Min.	Median	Mean	Max.	St. Dev.
Other Current Violations	0	0	1.33	44	2.43	0	1	3.49	42	5.09
Unclass Current Violations	0	0	0.00	5	0.03	0	0	0.00	0	0.00
Total Current Violations	0	1	2.47	150	3.98	0	3	6.81	70	8.57
Serious Initial Penalty	0	0	971.04	442,150	3,075.81	0	1,800	3,169.50	52,000	4,887.22
Willful Initial Penalty	0	0	129.50	429,000	4,194.43	0	0	268.54	70,000	3,953.84
Repeat Initial Penalty	0	0	231.93	403,200	3,130.26	0	0	793.56	110,360	6,315.02
Other Initial Penalty	0	0	25.84	10,163	197.16	0	0	177.43	5,000	774.84
Unclass Initial Penalty	0	0	0.55	35,000	124.60	0	0	0.00	0	0.00
Total Initial Penalty	0	0	1,358.86	731,790	6,901.08	0	2,100	4,409.03	134,310	10,122.25
Serious Current Penalty	0	0	547.79	184,160	1,749.94	0	900	1,629.17	21,150	2,372.93
Willful Current Penalty	0	0	53.61	280,000	2,228.84	0	0	0.00	0	0.00
Repeat Current Penalty	0	0	119.29	403,200	1,999.27	0	0	368.58	40,080	2,527.94
Other Current Penalty	0	0	25.51	25,000	201.19	0	0	98.09	4,500	440.91
Unclass Current Penalty	0	0	6.67	119,720	681.78	0	0	0.00	0	0.00
Total Current Penalty	0	0	755.48	431,100	4,083.52	0	1,020	2,095.85	53,460	3,918.85
Total FTA Amount	0	0	16.96	132,000	877.44	0	0	27.33	10,687	540.46

SOURCE: Author analysis based on data from OSHA, 2019, and data from the Michigan surveillance program.

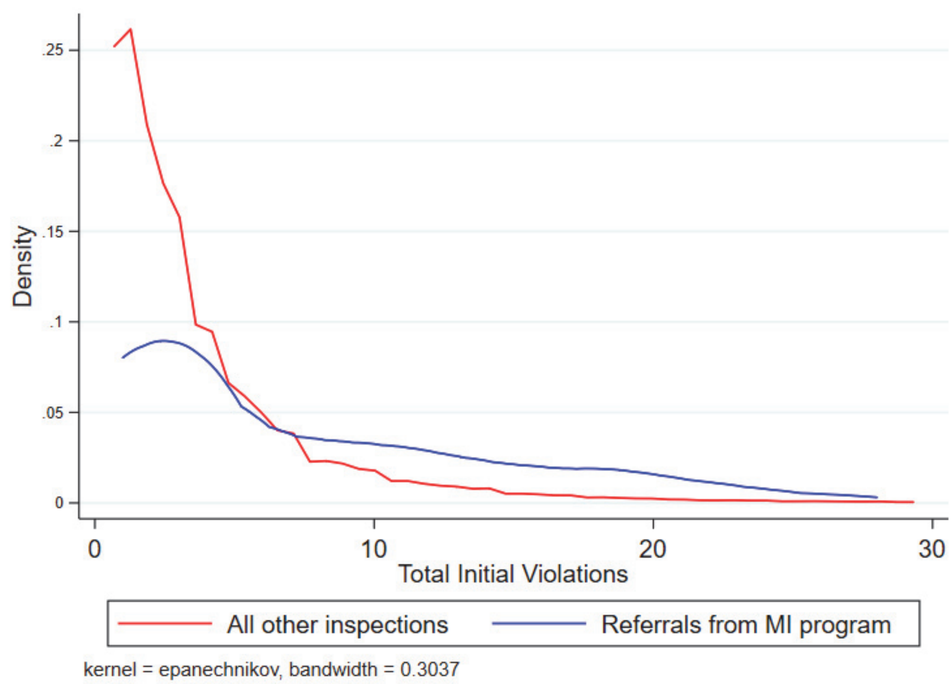
Table 4.4. Descriptive Statistics for Outcome Variables by Type (Numbers of Violations and Dollars of Penalty)

	Planned				Complaint				Referral				All Other			
	Other Insps.		Mich. Surv.		Other Insps.		Mich. Surv.		Other Insps.		Mich. Surv.		Other Insps.		Mich. Surv.	
Variable	**Med.**	**Mean**	**Med.**	**Mean**	**Med.**	**Mean**	**Med.**	**Mean**	**Med.**	**Mean**	**Med.**	**Mean**	**Med.**	**Mean**	**Med.**	**Mean**
Total Initial Violations	1	2.74	8	10.08	1	2.26	1	2.50	1	1.48	1	1.37	1	1.33	1	2.21
Total Current Violations	1	2.71	8	9.84	1	2.22	1	2.50	1	1.44	1	1.36	1	1.28	1	1.95
Total Initial Penalty	0	1,115.41	1,800	4,428.17	200	1,730.99	2,100	6,184.38	500	2,575.48	2,750	3,996.00	0	2,250.71	400	5,910.53
Total Current Penalty	0	616.02	900	2116.00	100	973.03	1,488	3,222.88	250	1,392.03	1,300	2,102.40	0	1,284.63	100	1,317.63

SOURCE: Author analysis based on data from OSHA, 2019, and data from the Michigan surveillance program.

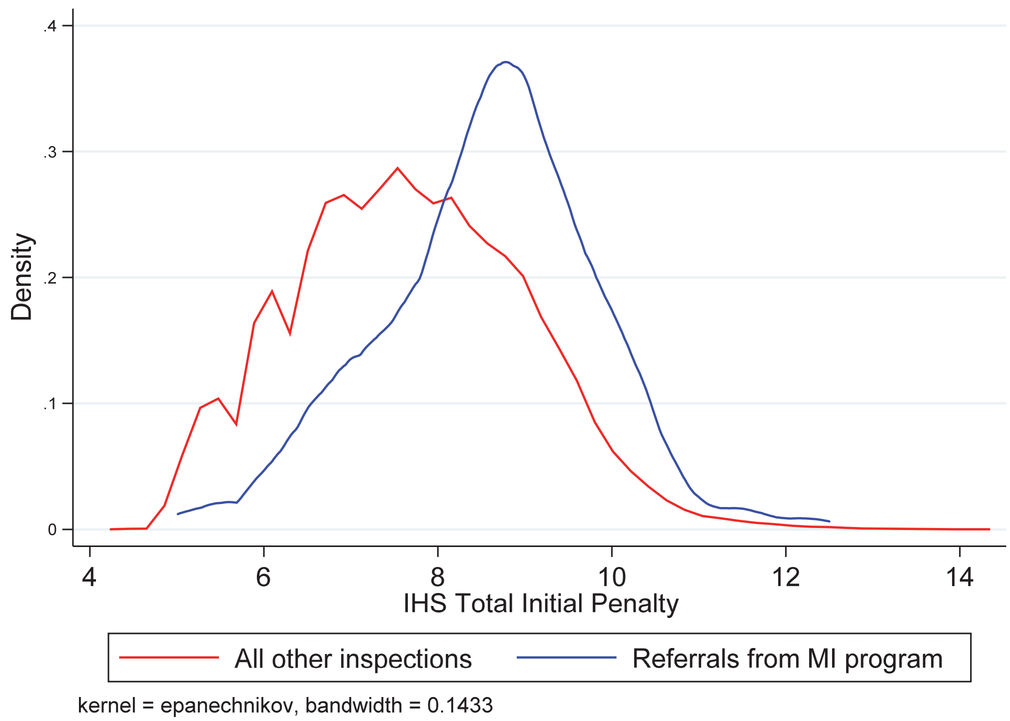
Also of note in Table 4.3 is that the distributions of these variables are highly skewed, containing many zeros but with large counts or dollar amounts at the upper end of the distribution. To dampen the effect of outliers on their outcome measures and get better estimates of the average effect of a program or intervention, economists and other social scientists often transform their data using natural logarithms or use nonlinear models that better approximate the distribution of the variables. Since the natural logarithm of zero is not defined, such a transformation will not work with the violation and penalty data as we would lose a large portion of our sample. An alternative transformation that has a similar interpretation as taking the natural logarithm and can deal effectively with zero-value outcomes is the inverse hyperbolic sine transformation (IHS), $sinh^{-1}(x) = \ln{(x + \sqrt{1 + x^2})}$. For additional information on this transformation see Bellemare and Wichman (2019). We apply this transformation to total initial penalties to get a better sense of the distribution of this variable. Figure 4.4 shows the distribution the IHS of the total initial penalty for inspections from the surveillance program and other inspections, excluding observations with zero values to focus on the variation in the outcome. As can be seen,

Figure 4.3. Distribution of Total Initial Violations from Surveillance Program Referrals and All Other Inspections in Michigan



SOURCE: Author analysis based on data from OSHA, 2019, and data from the Michigan surveillance program.
NOTE: Includes only nonzero observations and observations with violation counts less than 30.

Figure 4.4. Distribution of the IHS of Total Initial Penalty Size from Surveillance Program Referrals and All Other Inspections in Michigan



SOURCE: Author analysis based on data from OSHA, 2019, and data from the Michigan surveillance program.
NOTE: Distribution of the IHS of total initial penalty for observations with nonzero total initial penalties from the Michigan referral program and all other inspections.

the distribution of initial penalties from the inspections based on the Michigan amputation referral work is shifted to the right, with a higher mean and median. We will see this same pattern in our regression results below, which use a nonlinear Poisson model to better approximate the distribution of the data.

Are Violations and Penalties a Good Measure of Inspection Effectiveness?

The ultimate goal of the Michigan amputation surveillance program is to increase worksite safety and to decrease the number of work-related amputations in the state, not to specifically increase violations or penalties assessed by MIOSHA.[96] We used these proximate outcomes as a way to measure the effectiveness of inspections generated by the program for two reasons. First,

[96] Inspections may also be important for other reasons and number of citations or amount of penalties accessed do not necessarily capture the full value of inspections according to MIOSHA (Rocskay interview; Kalinowski interview).

as discussed, amputations are rare events and, given the scope of the program, we are unlikely to see direct results on the number of amputations in the data. Second, given the number of MIOSHA inspectors and the number of worksites in Michigan, inspections that find more violations are likely a good use of agency resources. Note that in defining an "effective" inspection as one that identifies more violations or accesses a higher amount of penalties than other inspections we are not taking into account the various inputs or other potential outputs that would go into a fully specified economic analysis of inspection activity.

While we cannot look at ultimate outcomes, we can observe the number of violations found and the amount of monetary penalties accessed from each inspection. As measures that MIOSHA sought to actively target, these outcomes would be problematic.[97] Incentivizing OSHA inspectors based on these metrics might cause them to issue additional violations or assess higher penalties in order to make their inspections appear more effective. While an overall decrease in the number of violations found would be good for society, indicating safer worksites, perversely, this success would lead to inspections appearing to be less effective if total violations and penalties were used as measures of success for OSHA.[98]

However, we believe that these are good outcomes for the purposes of the current study. We believe that MIOSHA inspectors are not incentivized to inflate these numbers, and their pay and prestige within the agency are not based on them. Assuming variation in hazardous conditions across different employers and given the limited number of MIOSHA inspectors for the number of establishments in the state, MIOSHA must allocate its scarce resources to find the worksites with the most or greatest number of hazardous conditions. Total violations and penalties per inspection seem like a reasonable proxy under these conditions. For instance, assume a world in which there are 20 unsafe practices spread across ten employers and only one MIOSHA inspector who can inspect two employers. If violations are spread equally across all employers, then it does not matter which employers are inspected. However, if 15 violations are committed by one employer, five by another, and the rest of the eight employers commit zero violations then the optimal action of the inspector would be to inspect the two employers with the highest

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[97] OSHA has similarly struggled with how to measure effectiveness of enforcement. The traditional system mandated that a certain number of inspections were performed in a given office per year. This system may have incentivized field offices away from performing longer, more complex inspections such as process safety inspections of oil refineries since they would take up lots of resources but only increase the inspection count number by the same amount as a simple, quick inspection. In 2015, OSHA created a system based on "Enforcement Units" to try to ensure that important but time-consuming inspections were not disincentivized in their measurement system. See Michaels, 2015.

[98] Note that violations as a metric of success for inspections might have different implications if one is comparing violations cross-sectionally (across inspections at a given point in time) versus longitudinally (across time). It may be unambiguously good for inspections to find more violations when comparing groups of inspections cross-sectionally. Longitudinally, increasing numbers of violations might result from increasing hazards or from improved targeting or thoroughness of inspections.

number of violations. If no information is available ex-ante, then the inspector has a 10-percent chance of finding one of the employers and a 2-percent chance of randomly finding both of the employers with the highest number of violations. We view the surveillance program as increasing the probability of locating employers who are already committing violations. In our example, if a surveillance program helped to direct the MIOSHA inspector by limiting the set of employers or providing information on which employers were not in compliance, it would be more likely that the inspector would find the two employers with the highest number of hazardous conditions, thus leading to a more effective use of resources. Thus, if (1) violations and unsafe conditions that could lead to injuries exist and are unevenly distributed across worksites, (2) MIOSHA inspectors report and do not differentially create or manipulate violations or penalties,[99] and (3) the number of MIOSHA inspectors is limited and small compared with the number of worksites, then violations and penalties per inspection are a good measure of the effectiveness of an inspection.

Results of the Amputation Surveillance Program on Violations Found and Penalties Accessed

In this section we show descriptive regressions controlling for increasingly more factors to examine the difference between violations and penalties for inspections based on the Michigan amputation surveillance program and all other inspections.

Many inspections end with no violations or penalties assessed. In the Michigan data from 2003 to 2018, 39 percent of inspections have zero violations and 53 percent have zero penalties. However, inspectors are more likely to find violations and assess penalties in inspections originating from the Michigan amputation surveillance program than in a typical inspection. Among these inspections, only 17 percent resulted in zero violations and 20 percent resulted in zero penalties. One of the primary researchers of the program, Dr. Kenneth Rosenman noted, "It is amazing that even after injuries, most of the companies have not fixed the problem before an inspection happens, even though inspections happen 3–6 months after the incident occurs."[100] Dr. Rosenman takes this as evidence that inspections are important in creating change and that improvements in worksite safety would not happen due solely to the injury itself.

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[99] It is true that inspectors likely have some information before they visit including records of injuries and past inspections and they may be sensitized about what things to look for. This would be problematic for us if the differential information about worksites that came from the amputation surveillance program led workers to seek out or look for more violations during those inspections than they otherwise would. It is also true that if all workers manipulate then the relative counts could still provide a sense of where the greatest problems are. However, if individuals differentially manipulate and this is correlated with industries or types of inspections that they do, then violations are no longer a good measure of inspection effectiveness.

[100] Rosenman interview.

Results for Total Initial Violations

We chose to model violations and penalties using a Poisson regression framework. Santos Silva and Tenreyro (2006) showed that the parameters of log-linear models estimated by ordinary least squares (OLS) can lead to biased estimates of the true elasticities if heteroskedasticity is present. Log-linear models also cannot incorporate observations with zeros in the outcome variable. Both Poisson and negative binomial regression analyses are commonly used to model count data and to deal with the problem of zero-valued dependent variables. Because both the violation and penalty data have a large number of zero values, the data suffer from overdispersion. Poisson regression analysis produces consistent estimates regardless of any overdispersion, so long as the functional form is correctly specified. Not all negative binomial distributions have this property. For further discussion, see Winkelmann (2008), Wooldridge (2010), Cameron and Trivedi (2013), and Blackburn (2014).

Table 4.5 shows the incidence rate ratios of a Poisson regression of a variable with a value of 1 for an inspection originating from the Michigan amputation surveillance program and 0 otherwise on the total initial violations. Results are broadly similar when using total current violations and modeling the relationship using other functional forms (OLS, negative binomial, selection model). The table indicates that an inspection originating from the Michigan surveillance program results in approximately 2.8 times as many violations as a typical inspection. The size of this effect decreases to 2.6 when we control for the type of inspection, the scope of the inspection, whether it was a health or safety inspection, and the year of the inspection. We also include an indicator for whether the inspection was in one of the priority industries targeted specifically from September 2008 to 2012. Throughout the entire period of our data, 82 percent of surveillance inspections were in these industries compared with 19 percent for all other inspections. Even after 2012, 69 percent of surveillance inspections were in these industries compared with 18 percent of other inspections. Including this indicator decreases the effect of the Michigan surveillance program from 2.6 to 1.46, although it is still statistically significant at standard levels. This suggests that part of the effect of the program likely came through targeting inspections toward high-priority industries.[101] A smaller, though

[101] Target industries from September 2008 to 2012 include the following: 312 Beverage and Tobacco Product Manufacturing; 321 Wood Product Manufacturing; 326 Plastics and Rubber Products Manufacturing; 327 Nonmetallic Mineral Product Manufacturing; 331 Primary Metal Manufacturing; 332 Fabricated Metal Product Manufacturing; 333 Machinery Manufacturing; 336 Transportation Equipment Manufacturing; 423930 Recyclable Material Merchant Wholesalers; 561730 Landscaping Services. Before September 2008, the priority industries were based on SIC code rather than NAICS code, but they were broadly similar. Being in the targeted industry was not a specific criteria of the surveillance program after 2012, but MIOSHA still had high-priority industries in its strategic plan. Regressions using priority industries based on the 2014–2018 Strategic Plan produced an estimate of 1.60 for the Michigan surveillance program. Using an indicator for being in a priority industry in either 2008–2012 or 2014–2018 produced an estimate of 1.50. Including a separate indicator for each of the 2008–2012 priority industries produced an estimate of 1.44.

still large and statistically significant, effect of 1.3 is found when we include indicator variables for each industry separately. Helping OSHA to better target inspections in industries that are likely to produce higher violations can be viewed as a mechanism through which the program operates, so it is unclear if this should be controlled for when examining the effect of the program. This better targeting at the industry level is an outcome of the program. However, these results suggest that a simple rule targeting high-priority industries may have been sufficient to achieve higher violation counts and penalty amounts even without the amputation surveillance program.[102]

[102] In models where both are present, each is large and statistically significant, indicating that both factors lead to inspections with higher violations. However, the coefficient on the priority industry variable is larger than the coefficient on the Michigan surveillance program variable.

Table 4.5. Incidence Rate Ratios of Poisson Regression of Total Initial Violations with Increasing Controls, 2003–2018

	(1)	(2)	(3)	(4)	(5)	(6)
Total Initial Violations						
Mich. Surv. Program	2.79***	3.04***	2.70***	2.60***	1.46***	1.29***
	(0.18)	(0.18)	(0.15)	(0.14)	(0.08)	(0.07)
Type = Referral		0.50***	0.88***	0.93**	0.75***	0.63***
		(0.01)	(0.02)	(0.02)	(0.02)	(0.02)
Type = Complaint		0.82***	1.43***	1.30***	1.10***	0.87***
		(0.01)	(0.02)	(0.02)	(0.02)	(0.02)
Type = Accident		0.96	1.35***	1.10*	1.02	0.90*
		(0.04)	(0.06)	(0.05)	(0.05)	(0.04)
Type = Unprog Rel		0.57***	1.05	1.06	0.99	0.88**
		(0.02)	(0.04)	(0.04)	(0.04)	(0.04)
Type = Prog Related		0.68***	1.05	1.02	1.00	0.98
		(0.02)	(0.03)	(0.03)	(0.03)	(0.03)
Type = Follow-up		0.03***	0.05***	0.04***	0.03***	0.02***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Type = Prog Other		0.52*	0.83	1.03	0.81	0.66
		(0.14)	(0.21)	(0.27)	(0.22)	(0.15)
Type = Monitoring		0.00***	0.00***	0.00***	0.00***	0.00***
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Type = Other		0.28***	2.15***	2.21***	1.53*	1.52*
		(0.01)	(0.35)	(0.41)	(0.29)	(0.26)
Type = Un Prog Other		0.44***	0.81	1.03	0.79*	0.74**
		(0.05)	(0.09)	(0.12)	(0.09)	(0.08)
Type = Variance		0.10***	0.16***	0.15***	0.18***	0.19***
		(0.04)	(0.06)	(0.05)	(0.06)	(0.07)
Type = Fat/Cat		0.54***	0.83*	1.08	0.96	0.83
		(0.05)	(0.07)	(0.09)	(0.09)	(0.08)
Safety Inspection			1.70***	1.65***	1.64***	1.81***
			(0.02)	(0.02)	(0.02)	(0.03)

	(1)	(2)	(3)	(4)	(5)	(6)
Priority Industry					2.45***	
					(0.03)	
Constant	2.50***	2.75***	2.07***	2.90***	2.37***	0.00
	(0.01)	(0.02)	(0.03)	(0.07)	(0.05)	(0.00)
Scope FE	No	No	Yes	Yes	Yes	Yes
Year FE	No	No	No	Yes	Yes	Yes
NAICS FE	No	No	No	No	No	Yes
Mean Dep. Var. (Control)	2.50	2.50	2.50	2.50	2.50	2.50
N	86,136	86,136	86,136	86,136	86,136	86,136

SOURCE: Author analysis based on data from OSHA, 2019, and data from the Michigan surveillance program.
NOTES: Exponentiated coefficients; standard errors in parentheses.
Scope, year, and industry (NAICS) fixed effects (FE) are included in the regressions where indicated. The constant term represents mean violations for the left-out group in the regressions. Thus, in regression (4), for example, the constant is the number of violations found in nonsurveillance, type = planned, scope = complete inspections in 2003. The mean of the dependent variable for observations that do not come from the Michigan Surveillance Program (control) is also included.
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Results for Total Initial Penalties

Table 4.6 shows the incidence rate ratios of a Poisson regression of a dummy for an inspection originating from the Michigan amputation surveillance program on the total initial penalties.[103] As with the total initial violations data, we find large differences between typical inspections and the inspections originating from the Michigan amputation surveillance program. Surveillance program inspections assessed 3.24 times as much in penalties as other inspections. This coefficient decreases to 2.68 when we control for type and then to 2.34 when we control for type, safety or health, and scope. When we control for type, safety and health, scope, and year, we find that surveillance program inspections assessed 2.45 times as much in penalties as did other inspections. As with the violation results, controlling for whether the observation was in a priority industry decreases the estimate, in this case to 1.50. All estimates are statistically significant at the 0.01 level.

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[103] We do not include separate dummies for each industry in these results because the Poisson model with industry fixed effects did not converge. However, in a simple OLS model results for penalties are similar to the results for violations. In the regression with no controls, surveillance program inspections assessed $3,050.17 more in penalties than other inspections. Including all controls plus industry fixed effects brings this amount down to $1,134.90. Both are statistically significant at the 0.05 level. Again, we believe that this is an outcome of the program—surveillance leads to better targeting of resources toward firms in industries that are more likely to be assessed (higher) penalties.

Table 4.6. Incidence Rate Ratios of Poisson Regression of Total Initial Penalties with Increasing Controls, 2003–2018

	(1)	(2)	(3)	(4)	(5)
Total Initial Penalty					
Mich. Surv. Program	3.24***	2.68***	2.34***	2.45***	1.50**
	(0.38)	(0.33)	(0.29)	(0.32)	(0.19)
Type = Referral		2.21***	2.61***	2.33***	1.77***
		(0.15)	(0.25)	(0.25)	(0.20)
Type = Complaint		1.54***	1.78***	1.83***	1.46***
		(0.06)	(0.12)	(0.14)	(0.12)
Type = Accident		7.13***	6.92***	8.00***	7.23***
		(0.90)	(0.93)	(1.16)	(1.08)
Type = Unprog Rel		2.10***	2.67***	2.53***	2.27***
		(0.24)	(0.36)	(0.36)	(0.32)
Type = Prog Related		1.48***	1.66***	1.66***	1.60***
		(0.09)	(0.12)	(0.13)	(0.13)
Type = Follow-up		0.34**	0.37*	0.40*	0.27**
		(0.13)	(0.14)	(0.16)	(0.11)
Type = Prog Other		3.28*	4.30**	3.51*	2.66
		(1.79)	(2.33)	(1.90)	(1.47)
Type = Monitoring		0.00***	0.00***	0.00***	0.00***
		(0.00)	(0.00)	(0.00)	(0.00)
Type = Other		0.69***	3.86***	3.67***	2.27***
		(0.03)	(0.78)	(0.69)	(0.49)
Type = Un Prog Other		1.85**	2.23***	1.74**	1.26
		(0.35)	(0.44)	(0.35)	(0.26)
Type = Variance		1.62	1.63	1.69	1.93
		(1.26)	(1.27)	(1.32)	(1.51)
Type = Fat/Cat		9.37***	9.42***	7.30***	6.40***
		(1.63)	(1.71)	(1.38)	(1.28)
Safety Inspection			1.65***	1.67***	1.61***
			(0.08)	(0.08)	(0.08)

	(1)	(2)	(3)	(4)	(5)
Priority Industry					2.73*** (0.12)
Constant	1,358.86*** (23.57)	1,121.04*** (24.28)	789.26*** (39.61)	732.51*** (62.36)	600.29*** (51.90)
Scope FE	No	No	Yes	Yes	Yes
Year FE	No	No	No	Yes	Yes
Mean Dep. Var. (Control)	1,358.86	1,358.86	1,358.86	1,358.86	1,358.86
N	86,136	86,136	86,136	86,136	86,136

SOURCE: Author analysis based on data from OSHA, 2019, and data from the Michigan surveillance program.
NOTES: Exponentiated coefficients; standard errors in parentheses. Scope and year fixed effects (FE) are included in the regressions where indicated. The mean of the dependent variable for observations that do not come from the Michigan Surveillance Program (control) is also included.
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Do Inspections Lead to Better Worksite Safety?

While these results suggest that the NIOSH-supported surveillance program in Michigan led to better targeting of inspections, we do not have the necessary data to see if these inspections led to the ultimate goal of better worksite safety. Many studies have attempted to measure the effectiveness of inspections and the link between worksite safety enforcement and fewer injuries.[104]

The two best studies on the effectiveness of inspections are Levine, Toffel, and Johnson (2012) and Li and Singleton (2019). The former compared randomly inspected establishments (409) in California with eligible but not chosen matched-control establishments (409). While they found no harm to employers from the inspections, they did find that inspected employers saw injury rates decline by 9.4 percent and injury costs from wage replacement and medical expenses decline by 26 percent compared with controls. They estimated that on average, inspections lowered employers' medical costs and lost earnings due to worksite injuries by about $355,000 over the next few years. Li and Singleton (2019) exploited a cutoff of OSHA's Site-Specific Targeting plan to estimate the effects of inspections with a fuzzy regression discontinuity using panel data on 61,702 unique establishments between 1996 and 2011. The authors reported that inspections decrease the rate of cases that involve days away from work, job restrictions, and job transfers in the calendar year immediately after the inspection cycle. They did not, however, find statistically significant effects for other outcomes such as death or medical attention beyond first aid (or for days away from work in some specifications) or in subsequent years. The authors speculated that a possible mechanism to explain their results would be that inspections "reduced the severity of cases that would otherwise require job restrictions or transfers to require only medical attention beyond first aid" (p. 734). As with all regression discontinuity designs, their results are local to the cutoff that they used; their cutoff targeted inspections at establishments with high rates of injuries.

Effects of Better Inspection Targeting

While our estimates are not causal, if we assume that inspections that occurred due to the Michigan amputation surveillance program would not have occurred but for the program and that resources utilized for these inspections would have been used to conduct inspections similar to the average inspection measured in our data had the program not existed, then we can provide some rough numbers of the effects of the program on these proximate outcomes. Under these

[104] For example, Gray and Mendeloff, 2005, found large effects of OSHA inspections on injuries in manufacturing plants but that the effects have declined from 1979 to 1998. Their estimates indicate that an OSHA inspection imposing a penalty reduced lost-workday injuries by about 19 percent in 1979–1985, 11 percent in 1987–1991, and a statistically insignificant 1 percent in 1992–1998. Among many others, see Foley et al., 2012, and Weil, 1996.

assumptions the program increased the number of violations discovered by about 96 violations per year (base rate of 2.5 violations per inspection × 2.6 times more violations per inspection found in surveillance inspections[105] × 24 surveillance inspections in a typical year minus the base rate of 2.5 × 24) and increased total initial penalties by approximately $47,300 per year (1,358.86 base rate × 2.45 for surveillance inspections × 24 surveillance inspections in a typical year minus the base rate of 1,358.86 × 24).[106]

Another way to consider the effects of targeting is to ask how many typical inspections would need to be performed to find the same number of violations as were found by the surveillance inspections. Nonsurveillance inspections find an average of 2.5 (median 1) violations per inspection. To find 96 violations would take about 38 inspections (96 based on the median instead of the mean) compared with the 24 surveillance inspections that were performed. Viewed through this lens, the program "saved" 14 (72) inspections per year along with their associated costs and still found the same number of violations. Calculating similar numbers based on total penalties yields a saving of about 11 inspections per year (the median total initial penalty is zero, so this calculation is less meaningful for that statistic).

Note that these estimates are based on the current size of the program. There may be diminishing returns to additional inspections in this area; that is, if more amputations are found and more inspections are done based on them then the marginal benefit of these additional inspections may be lower than the benefit of current inspections. While we would be hesitant to extrapolate our estimates out of sample, we note that the surveillance program currently makes up only a tiny fraction of total inspections and that the program would likely need to grow by well over an order of magnitude to affect the marginal benefit of an additional surveillance inspection.

We do not have a way of credibly estimating how these more effective inspections translate into lower injury rates or medical costs. Levine, Toffel, and Johnson (2012) estimated that a random inspection led to a reduction in injuries in the five years after a workplace inspection, which would then reduce medical costs and lost earnings by roughly $355,000 (in 2011 dollars or $405,000 in 2019 dollars). The authors estimated smaller (at most $221,000) or no costs to the employers. As noted, the inspections that we study are not additional inspections but

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[105] The estimate of the model with controls for priority industries can be used here instead if one does not consider industry targeting an explicit benefit of the program.

[106] Note that while a full cost analysis of the program was not the focus of this report, it is not an expensive program from the research side, with costs of less than $30,000 per year (Rosenman interview). However, the full net benefits of the program depend upon the inspection activities and the compliance activities of employers. We do not know what the costs are, if any, of changing the mix of inspections. We also do not have information on the cost of additional compliance activities for employers beyond the penalty fees. Further, we do not have estimates of future benefits to employers of avoiding injuries besides the estimates from other studies, which we discuss below. These additional pieces of information would be necessary to estimate the full net benefits of the program.

inspections that find more violations and penalties. However, if we assume that a more effective inspection leads to results similar to what Levine, Toffel, and Johnson (2012) estimated for an inspection taking place at all, and that a less effective inspection would have led to no reductions in injuries, then the 24 additional surveillance inspections per year would lead to $9.72 million dollars of saved costs and lost earnings per year of the program. To the extent that the very act of conducting an inspection regardless of the number of violations found or penalties assessed leads to the findings of Levine and colleagues, the dollar benefits of a more effective inspection from lower injury rates would be lower. Note also that the Levine, Toffel, and Johnson (2012) study was in a different geography (California) and was not specifically studying targeted inspections, so caution is warranted in extrapolating their point estimates. Establishing better evidence of the causal effect of different types and modes of inspections in various geographies is an important area for future research.

What Information Would Help to Better Measure Benefits

As discussed above, these estimates are likely an underestimate of the true effects of the program. To quantify the true benefits of the Michigan amputation surveillance program, we would need to know how many amputations the program helped to prevent.[107] We could then use estimates of the costs of an amputation (medical costs and the costs of lost work labor or disability-adjusted life years) to estimate the benefits that the program provided in terms of amputations avoided. As previously discussed, the available data do not permit credible estimation of the causal effect of the program on amputations.

Better information on how inspections alone, as well as the number and types of violations identified and the penalties assessed during an inspection translate into lower injury rates is crucial to estimating the benefits of surveillance programs. Outcomes that are relatively rare, such as amputations, are also difficult to study in a causal framework. Figuring out if and how rates of different injuries are correlated, or finding other, more common proxies that lead to or reduce ultimate outcomes may be a fruitful area of future research as these more common outcomes might be easier to study using traditional causal methods such as regression discontinuity, regression kink, difference-in-difference, or randomized controlled trials.

[107] To better estimate the causal benefits of the Michigan surveillance program, one could set up a randomized controlled trial where referrals from the program were randomly chosen to receive an inspection. Worker injury rates (especially amputation rates) at both those chosen for the random inspections and those not chosen would be monitored for several years after the inspections occurred to determine whether the inspection resulting from the surveillance program led to greater worker safety at the worksites that received the inspections. Because amputations are relatively rare, the program would likely have to be conducted over a very large geography or over many years to have enough statistical power to see the effects of the program on amputations.

There is a further value in the information provided by the Michigan surveillance program. Although it is well known that the BLS SOII statistics underestimate injury counts, the program in Michigan was able to provide much more precise information on the number of amputations in Michigan each year and to better identify the worksites, activities, and conditions where they are most prevalent. This information alone is important in better understanding the extent of the problem and how to better stop future amputations. As with the direct reduction in amputations from inspections, we are not able to quantify this important potential indirect benefit of the Michigan program. Better tracking and understanding of information networks and how surveillance ideas spread over time and across geographies would be useful to ascertain how this information is used and how it benefits society.

It is also possible that inspections from the surveillance program had spillover effects. There are at least three kinds of potential spillovers that might be relevant: within an employer, between employers, and across states. Although inspectors are looking for violations that caused injuries related to amputations, they may find other violations that prevent other injuries or, by mitigating the risk of an amputation, they may also decrease the risk of other types of injuries. Information on how often nontargeted violations are found during targeted inspections as well as data on whether employers respond to inspections by mediating hazards that were not part of the inspection could help to better understand this potential spillover effect.

Inspections may also encourage better safety practices in employers not inspected through contacts between plant managers, safety inspectors, or other employees. There is evidence that OSHA press releases of violations in federal OSHA states caused other employers to improve their compliance and experience fewer occupational injuries, suggesting a possible deterrence effect (Johnson, 2019; see also Weil, 1996). More information on how and why employers respond to OSHA enforcement that is not directly targeting them would allow for better measurement of these spillover effects.

Finally, as discussed, the Michigan program helped to inform and influence the creation of similar programs in other states such as Massachusetts and may have contributed to a federal law change in 2015 that required employers to report amputations. To get a full measure of the benefits of the Michigan program, we would also want to add to the direct benefits from Michigan some percentage of the benefits found in other states, such as Massachusetts, that were influenced by the Michigan program as well as some share of the benefits from the 2015 federal rule change. Documenting and detailing exactly how the Michigan program influenced the Massachusetts surveillance program and how important the public comments from the Massachusetts Department of Health were on the creation of the federal law would help to better understand the value of the Michigan program as a model for other jurisdictions.

Currently, we cannot quantify these three distinct types of spillover effects. We suggest this as an important area of future research.

Conclusion

A Michigan amputation surveillance program funded by NIOSH led to inspections that found more violations and assessed higher monetary penalties than typical inspections in the state between 2003 and 2018. While our estimates are not causal, it is likely that the surveillance program helped MIOSHA to better target inspections, especially through better industry targeting, leading to a more effective allocation of scarce resources such as inspection personnel. Inspections from the surveillance program found 2.60 times as many violations as other inspections and assessed approximately 2.45 times the amount of a typical inspection in monetary penalties.

The Michigan surveillance program may have led to spillover effects within the employers that were inspected and across employers. Although we are not able to quantify the benefits, we have direct evidence that the Michigan program substantially influenced other state programs, such as the one in Massachusetts. The program also provided better information on the extent of amputations in Michigan and in which industries and employers amputations had occurred that were not reported in other sources.

Currently, we cannot quantify the benefit of the program on worker safety and reduction in amputations or measure the spillover effects of the program. We also do not know if the results from Michigan could be extrapolated to other states or would apply to offices administered by federal OSHA.

While more data are necessary to fully quantify the benefits of surveillance programs and to establish a causal link between surveillance, inspections, and worker safety, our preliminary analysis suggests that NIOSH-supported surveillance programs likely have positive benefits to society.

5. Conclusion

Summary of Selection Process Findings

In 2017, NIOSH asked the RAND Corporation to develop an approach for estimating the economic benefit of its research and services activities and illustrate its use through three exploratory case studies. Miller et al. (2017) provided such an approach and illustrated its use through three exploratory case studies. This report builds upon that work by developing a process for selecting case studies for evaluation, applying that selection process to a list of ten potential case studies, and selecting three case studies from this list for detailed analysis.

NIOSH identified ten potential case studies, and RAND traced the elements of these case studies from the input hazard to the potential changes in health outcomes for workers and other affected individuals. In parallel, RAND identified attributes of cases studies that NIOSH might use to identify which cases to evaluate in further detail:

- **Feasibility.** There must be enough information available to anticipate the ability to establish and quantify the link between NIOSH activities and worker outcomes without extensive new data collection.
- **Impact.** This is defined in terms of (a) the number of potentially affected workers, (b) the extent to which there is evidence that control measures resulting from on NIOSH's work are actually implemented, and (c) the actual or anticipated reduction of risk resulting from the implementation of these control measures.
- **Attribution.** There must be clear evidence that changes in worker safety and health occurred in response to NIOSH efforts.
- **Balance.** When taken together, the cases must represent a diversity of program areas.
- **Institutional priorities.** The cases must represent current areas of particular interest to NIOSH.

Based on these attributes, we selected three case studies: Personal Dust Monitors for Coal Miners, Improved Ambulance Design, and Improved Amputation Surveillance.

Summary of Case Study Findings

In the Personal Dust Monitors for Coal Miners case, we found NIOSH's activities, which included awarding research grants, collaborating with industry and labor in testing and developing prototypes, disseminating research findings, and conducting outreach to miners, played a major role in the development and adoption of CPDMs for coal miners. Without NIOSH's contribution, the achieved reductions in exposure to respirable coal mine dust may not have been as successful and improvements in workplace practices based on corrective actions linked to CPDMs would have been less likely to occur.

- We estimate the avoided medical costs and productivity losses for cases of fatal and nonfatal respiratory disease due to the reduction in exposures to respirable coal mine dust after the adoption of CPDMs ranged from $3.6 million to $8.0 million on an annualized basis over 65 years, depending on the attribution of fatal cases avoided by age 73 or 85 and whether a 3-percent or 7-percent discount rate is used.
- We estimate the economic benefits based on WTP estimates associated with risk reductions in fatal and nonfatal respiratory disease ranged from $10.4 million to $25.3 million per year, depending on the attribution of fatal cases avoided by age 73 or 85 and whether a 3-percent or 7-percent discount rate is used.

In the Improved Ambulance Design case, we found NIOSH's impact on ambulance design has been the result of a steady stream of partnerships with stakeholders. NIOSH has focused on improving the design of the patient compartment and its contents, both by working directly with manufacturers and by collaborating with standard-setting organizations. NIOSH continues to play a pivotal role in these partnerships, and many of the design changes may not have happened without NIOSH's involvement. We estimate the benefits associated with three different sets of assumptions about the effectiveness of the ambulance redesign in preventing injuries or reducing injury severity: the patient compartment becoming as safe as the back seat of a standard four-door passenger vehicle, the patient compartment becoming as safe as ambulance driver position, or improvements in patient compartment safety being consistent with literature on seat belt effectiveness in similar vehicles.

- If the ambulance redesign causes the patient compartment of ambulances to become as safe as any of the sets of assumptions we modeled, this could result in an annualized benefit that ranges from $2.5 million to $8.0 million from 2017 to 2050, depending on the modeling assumptions and whether a 3-percent or 7-percent discount rate is used. Benefits per year increase over time.
- If the ambulance redesign causes the patient compartment of ambulances to become as safe as any of the sets of assumptions we modeled, this could result in between $24 million and $74 million in avoided VSL losses from 2017 to 2050, depending on the modeling assumptions and whether a 3-percent or 7-percent discount rate is used. Benefits per year increase over time.
- There are many uncertainties associated with these estimates, and the ultimate impact could vary significantly. Due to data limitations, these estimates examine only injuries associated with collisions, and do not include injuries associated with noncollision events.

In the Improved Amputation Surveillance case, we found that a Michigan amputation surveillance program funded by NIOSH led to referrals that found more violations and assessed higher monetary penalties than typical inspections in the state between 2003 and 2018. While our estimates are not causal, it is likely that the surveillance program helped MIOSHA to better target inspections, leading to a more efficient allocation of scarce resources, such as inspection personnel. Inspections from the surveillance program found 2.60 times as many violations as other inspections and assessed approximately 2.45 times the amount of a typical inspection in monetary penalties. The Michigan program substantially influenced other state programs, such as the one in Massachusetts. The program also provided better information on the extent of amputations in Michigan and in which industries and firms amputations had occurred that were not reported in other sources.

- While our estimates are not causal, if we assume that inspections that occurred due to the Michigan amputation surveillance program would not have occurred but for the program and that resources utilized for these inspections would have been used to conduct inspections similar to the average inspection measured in our data had the program not existed, then we can provide some rough numbers of the effects of the program on these proximate outcomes. Under these assumptions the program increased the number of violations discovered by about 96 violations per year and increased total initial penalties by approximately $47,300 per year.
- The available data do not enable us to quantify the benefits of the program on worker safety and reduction in amputations, or to measure the spillover effects of the program. While more data are necessary to fully quantify the benefits of surveillance programs and to establish a causal link between surveillance, inspections, and worker safety, our preliminary analysis suggests that NIOSH-supported surveillance programs likely have positive benefits to society.

Lessons and Limitations

One lesson from the case study selection exercise is that quickly determining feasibility is challenging; we ran into many challenges that would have been difficult to foresee without initiating the analytic process. The availability of data is critical, but determining what data are needed and what data are available can be time-consuming steps. For example, in the Improved Ambulance Design case, the impacts have not yet occurred and there are too many factors that influence the potential outcomes to predict with certainty what the benefits will be, hence we provide several estimates of what the benefits might be under a variety of assumptions. In the Improved Amputation Surveillance case, data were insufficient for estimating avoided direct medical costs and productivity losses or broader societal benefits. We cannot reach conclusions about whether the cases we did not evaluate would have been more or less feasible than anticipated. The purpose of identifying a case study selection process is to help NIOSH more easily identify cases for future analysis. We believe that determining infeasibility due to clear lack of data is likely easier than determining feasibility, as more nuanced challenges only arise upon detailed evaluation of a potential case.

The Benefits of NIOSH Research Activities

In combination with the results from Miller et al. (2017), this report increases the sample of evaluated case studies of NIOSH research activities. That report found other NIOSH research was associated with millions of dollars in avoided medical costs and productivity losses. The case study on Supporting Development of Silica Controls in Asphalt Pavement Milling found NIOSH research was associated with an annualized value of $4.9 million in 2016 dollars in avoided medical costs and productivity losses for fatal lung cancers, and from $304 million to $1.1 billion per year in VSL estimates. The case study on Building and Disseminating Evidence on Cancer Risk Among Firefighters found NIOSH research was associated with an annualized value of $71 million in 2016 dollars in avoided medical costs and productivity losses, and approximately $1 billion per year in VSL estimates for all associated fatal and nonfatal diseases. The case study on Assessing and Disseminating Impacts of Ohio Safety Grants found NIOSH research was associated with $4 million to $7 million per year in nominal dollars in avoided workers' compensation costs, $7 million to $11 million in productivity gains per year, and from almost $700,000 to over $16 million of avoided uncompensated wage loses per year. The cases examined in these reports were not selected at random, and were in part selected because they were anticipated to have large impacts. Nevertheless, they show that there are many NIOSH research activities that result in millions of dollars in benefits each year for a wide array of workforces. Although we do not examine the costs associated with these NIOSH research efforts, we believe that the returns on investment are likely quite favorable because costs of implementing these programs can be significantly smaller than the benefits.

Appendix. Additional Detail for the Dust Monitor Case Study

This appendix provides additional detail for the Personal Dust Monitors for Coal Miners case study in Chapter 2. This supporting material corresponds to Steps 3, 4, and 5 of the analysis.

Measurement of Baseline Average Respirable Coal Dust Levels

Figure A.1 provides the mathematical formula for the calculation of the baseline average dust concentration measurements described in Step 3. The adjusted and supplemental estimates were developed in the Mine Safety and Health Administration's *Quantitative Risk Assessment in Support of the Final Respirable Coal Mine Dust Rule* (QRA) (MSHA, 2013). While MSHA's assessment relied on the 2008 coal dust samples (as shown in the figure), in this report we rely on the 2010 to 2015 inspector and operator samples.

Calculation of Excess Risk of Morbidity and Mortality

Step 4 of the analysis in Chapter 2 estimates the reduction in the number of illnesses and deaths associated with the adoption of CPDMs. The following tables report estimates of the excess risk of morbidity and mortality for each group of workers (described in Step 2) associated with the baseline exposure levels and reduced exposure levels after the adoption of CPDMs (described in Step 3). The exposure risk models used in Step 4 are described in detail in Appendices I, J, and K of MSHA's QRA (MSHA, 2013).[108] Tables A.1–A.5 report the excess risk of morbidity or mortality under the baseline dust concentration measurements shown in Chapter 2 (Table 2.4). Tables A.6–A.10 report excess risk of morbidity or mortality at reduced exposure levels after the adoption of CPDMs. The estimates in the second set of tables can be subtracted from the baseline levels in Tables A.1–A.5 to calculate the impact of CPDMs on the excess risk of respiratory disease due to coal mine dust (measured per 1,000 workers).

[108] Due to the relative complexity of the exposure risk models, we do not reproduce them here but refer to the detailed equations provided in the appendices to MSHA's QRA.

Figure A.1. Estimation of Baseline Average Exposure Levels

Estimation of Current Average Exposure Levels (Adjusted and Supplemented Estimates)

$\Re$ is defined as 0.5 mg/m^3 for Part 90 miners and 1.0 mg/m^3 for all other job-categories.

For each job-category in a given work location:

Let K_g denote the number of valid, 1st-day MSHA (government) dust concentration measurements collected in 2008; let K_o denote the number of valid operators' periodic and support dust concentration measurements collected in 2008 for the same job-category and work location.

Let $\sum X_g$ denote the sum of the K_g MSHA measurements, and let $\sum X_o$ denote the sum of the K_o operator measurements.

Let $$\tilde{\mu} = \begin{cases} \dfrac{\sum X_g + \sum X_o}{K_g + K_o} & \text{if } K_g < 2 \text{ or if } \dfrac{\sum X_g}{K_g} < \dfrac{\sum X_o}{K_o} \\ \dfrac{\sum X_g}{K_g} & \text{otherwise} \end{cases}$$

Let $\overline{XS} = \dfrac{\sum_{X_g > \Re}(X_g - \Re) + \sum_{X_o > \Re}(X_o - \Re)}{k_g + k_o}$, where k_g and k_o are the number of MSHA and operator samples exceeding $\Re$, respectively.

Let $$\overline{XS}_o = \frac{\sum_{X_o > \Re}(X_o - \Re)}{k_o}$$

Let K denote the number of samples used to form $\tilde{\mu}$ (i.e., either K_g or K_g+K_o), and let k denote how many out of these K samples exceed $\Re$.

Then the estimate of the current average dust concentration level for the specified job-category at the given work location is:

$$\tilde{\tilde{\mu}}_{\text{now}} = \begin{cases} \tilde{\mu} & \text{if } \overline{XS}_o \le \overline{XS} \\ \dfrac{K \bullet \tilde{\mu} + k \bullet (\overline{XS}_o - \overline{XS})}{K} & \text{if } \overline{XS}_o > \overline{XS} \end{cases}$$

SOURCE: MSHA, 2013, Appendix F.

Table A.1 reports estimates based on the Attfield and Seixas (1995) logistic regression models of excess risk of CWP1+, CWP2+, and PMF for each recurrency class at low/medium rank coal mines. Table A.2 reports estimates of excess risk of CWP1+, CWP2+, and PMF under the baseline exposure conditions for each recurrency class at high rank coal mines.

Table A.3 reports estimates of excess risk of COPD (i.e., severe emphysema corresponding to a FEV1 of less than 65 percent of the predicted normal value) using Kuempel, Vallyathan, and Green's (2009) logistic regression model for each recurrency class. This model does not account for differences between low- and high-rank coal. The projected excess risk of severe emphysema in the model increases for nonwhite miners and for smokers. For example, MSHA found the projected excess risk for nonwhite cutting machine operators was 50 percent higher than for white miners in the same occupation (MSHA, 2013). It was not feasible to estimate the distribution of coal miners according to demographic characteristics across specific WLs (i.e., by occupation, mine, and work area). NIOSH (2012a) estimates that approximately 96 percent of workers at coal mines are white. Based on the National Health Interview Survey (NHIS), CDC estimates that 20.1 percent of workers in the mining industry are current smokers (using 2014 to 2018 data) and this figure may be higher for nonwhite miners.[109] Only one of the exposure risk studies used in the analysis incorporates information on smoking; however, the model parameters require an estimate of the average number of cigarette packs smoked per day. This information is available in some NHIS reports, but may not be specific to underground coal miners. Since we do not have more detailed demographic data for the affected population, we calculate excess risk for nonsmoking, white miners to produce a more conservative estimate.[110]

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[109] Based on information provided by NIOSH's Respiratory Health Division on October 15, 2019. Current smokers are defined as those who smoked at least 100 cigarettes during their entire life and currently smoke.

[110] Since the incremental elevated excess risk due to smoking only factors into one of the morbidity models, Kuempel, Vallyathan, and Green (2009), and smokers are a minority of the population, incorporating this added risk factor is unlikely to significantly impact the overall estimates in this report. However, we note that the additional excess risk may be significantly higher for workers smoking two packs a day as opposed to workers smoking less than half a pack per day, for example.

Table A.1. Estimated Excess Risk of CWP by Age 73 After 45 Years of Occupational Exposure at Baseline Exposure Levels at Low/Medium Rank Bituminous Coal Mines (per 1,000 Workers)

	Low-Recurrence			Mid-Recurrence			High-Recurrence		
Occupation	CWP 1+	CWP 2+	PMF	CWP 1+	CWP 2+	PMF	CWP 1+	CWP 2+	PMF
Auger Operator	58.5	33.1	17.0	75.4	43.3	22.0	167.3	103.5	51.5
Continuous Miner Operator	46.2	25.9	13.3	76.9	44.2	22.5	113.7	67.4	33.9
Cutting Machine Operator	51.0	28.7	14.7	87.2	50.6	25.6	132.2	79.5	39.8
Drill Operator	42.1	23.5	12.1	105.0	61.8	31.1	–	–	–
Electrician and Helper	28.8	15.9	8.3	73.5	42.2	21.5	–	–	–
Laborer	35.9	19.9	10.3	166.0	102.6	51.0	204.5	130.3	64.5
Loading Machine Operator	26.6	14.7	7.6	–	–	–	–	–	–
Longwall Headgate Operator	57.7	32.6	16.7	90.9	52.9	26.8	141.6	85.8	42.9
Longwall Jacksetter	62.6	35.6	18.2	105.7	62.2	31.3	163.0	100.5	50.0
Longwall Tailgate Operator	80.7	46.5	23.6	109.6	64.7	32.6	155.7	95.4	47.5
Mechanic and Helper	35.5	19.7	10.2	99.4	58.2	29.4	–	–	–
Mobile Bridge Operator	46.5	26.1	13.4	88.0	51.0	25.9	94.6	55.2	27.9
Roof Bolter	44.0	24.6	12.7	84.9	49.1	24.9	125.4	75.0	37.6
Scoop Car Operator	46.8	26.2	13.5	119.1	70.8	35.6	186.2	117.0	58.0
Section Foreman	40.6	22.6	11.7	179.7	112.3	55.7	376.9	275.8	137.6
Shuttle Car Operator	38.0	21.2	10.9	91.1	53.0	26.8	148.2	90.3	45.0
Uni-Hauler Operator	34.5	19.1	9.9	126.1	75.4	37.8	–	–	–
Utility Man	45.8	25.7	13.2	134.6	81.1	40.6	–	–	–
All Other Underground Jobs	49.0	27.5	14.2	138.1	83.4	41.7	346.7	247.5	122.9
Part 90 Miners	16.3	8.9	4.7	41.4	23.1	11.9	65.1	37.1	18.9

Table A.2. Estimated Excess Risk of CWP by Age 73 After 45 Years of Occupational Exposure at Baseline Exposure Levels at High Rank Bituminous or Anthracite Coal Mines (per 1,000 Workers)

	Low-Recurrence			Mid-Recurrence			High-Recurrence		
Occupation	**CWP 1+**	**CWP 2+**	**PMF**	**CWP 1+**	**CWP 2+**	**PMF**	**CWP 1+**	**CWP 2+**	**PMF**
Auger Operator	102.2	74.3	49.6	133.9	101.1	68.3	310.3	279.6	203.6
Continuous Miner Operator	79.6	56.3	37.3	136.8	103.7	70.1	207.6	170.0	118.1
Cutting Machine Operator	88.3	63.1	42.0	156.5	121.4	82.6	243.4	206.4	145.6
Drill Operator	72.1	50.5	33.4	190.7	153.4	105.9	–	–	–
Electrician and Helper	48.4	32.8	21.6	130.3	98.1	66.1	–	–	–
Laborer	60.9	42.0	27.7	307.9	276.9	201.4	378.7	360.4	272.1
Loading Machine Operator	44.6	30.1	19.7	–	–	–	–	–	–
Longwall Headgate Operator	100.6	73.1	48.8	163.5	127.8	87.2	261.3	225.4	160.3
Longwall Jacksetter	109.9	80.7	54.0	192.0	154.7	106.8	302.2	270.4	196.1
Longwall Tailgate Operator	143.9	110.0	74.6	199.6	162.1	112.2	288.3	254.9	183.6
Mechanic and Helper	60.3	41.5	27.4	179.9	143.1	98.3	–	–	–
Mobile Bridge Operator	80.1	56.7	37.6	157.9	122.6	83.5	170.7	134.4	92.0
Roof Bolter	75.5	53.1	35.2	152.0	117.2	79.7	230.2	192.7	135.2
Scoop Car Operator	80.6	57.1	37.8	217.9	180.3	125.8	345.5	320.6	237.7
Section Foreman	69.3	48.3	32.0	333.5	306.4	225.7	633.8	691.2	614.2
Shuttle Car Operator	64.7	44.9	29.6	163.9	128.1	87.4	274.1	239.3	171.2
Uni-Hauler Operator	58.4	40.1	26.4	231.5	194.1	136.2	–	–	–
Utility Man	78.7	55.6	36.9	247.9	211.2	149.3	–	–	–
All Other Underground Jobs	84.6	60.2	40.0	254.7	218.3	154.8	597.4	643.5	557.6
Part 90 Miners	26.9	17.7	11.5	70.8	49.5	32.7	114.6	84.6	56.7

Table A.3. Estimated Excess Risk of COPD by Age 73 After 45 Years of Occupational Exposure at Baseline Exposure Levels (per 1,000 Workers)

Occupation	Low-Recurrence	Mid-Recurrence	High-Recurrence
Auger Operator	37.3	47.4	100.9
Continuous Miner Operator	29.7	48.4	70.1
Cutting Machine Operator	32.6	54.5	80.8
Drill Operator	27.1	65.0	–
Electrician and Helper	18.8	46.3	–
Laborer	23.2	100.2	122.0
Loading Machine Operator	17.4	–	–
Longwall Headgate Operator	36.7	56.7	86.2
Longwall Jacksetter	39.8	65.4	98.4
Longwall Tailgate Operator	50.6	67.7	94.2
Mechanic and Helper	23.0	61.7	–
Mobile Bridge Operator	29.9	55.0	58.9
Roof Bolter	28.3	53.1	76.8
Scoop Car Operator	30.1	73.2	111.6
Section Foreman	26.2	107.9	222.3
Shuttle Car Operator	24.6	56.8	90.0
Uni-Hauler Operator	22.4	77.2	–
Utility Man	29.4	82.2	–
All Other Underground Jobs	31.4	84.2	204.1
Part 90 Miners	10.7	26.7	41.3

Table A.4 reports estimates of excess risk of death due to NMRD by age 73. This estimate is calculated in two steps. First, we use the Attfield and Kuempel (2008) proportional hazards model to estimate the relative risk based on coal rank and accumulated coal mine dust exposure for each exposure category. Second, we calculate the excess risk estimates by comparing the relative risk during each year of 45-year occupational history to the NMRD mortality rate in a reference population without occupational exposure.[111] Table A.5 reports estimates of excess risk of death due to NMRD by age 85. These estimates are, on average, two times the estimates of excess risk of death by age 73.

[111] Based on information provided by NIOSH's Education and Information Division on July 10, 2019.

Table A.4. Estimated Excess Risk of NMRD Mortality by Age 73 After 45 Years of Occupational Exposure at Baseline Exposure Levels (per 1,000 Workers)

	Low-Recurrence			Mid-Recurrence			High-Recurrence		
Occupation	**Low-/Med.-Rank**	**High-Rank Bituminous**	**Anthracite**	**Low./Med.-Rank**	**High-Rank Bituminous**	**Anthracite**	**Low/Med.-Rank**	**High-Rank Bituminous**	**Anthracite**
Auger Operator	3.0	9.7	–	4.0	10.9	–	8.8	16.8	–
Continuous Miner Operator	2.3	8.9	87.0	4.0	11.0	93.5	6.0	13.4	100.7
Cutting Machine Operator	2.6	9.2	–	4.6	11.7	–	7.0	14.6	–
Drill Operator	2.1	8.6	–	5.6	12.9	–	–	–	–
Electrician and Helper	1.2	7.6	83.1	3.9	10.8	92.8	–	–	–
Laborer	1.7	8.1	84.7	8.7	16.7	110.3	10.6	19.1	117.1
Loading Machine Operator	1.1	7.4	–	–	–	–	–	–	–
Longwall Headgate Operator	3.0	9.7	–	4.8	11.9	–	7.5	15.2	–
Longwall Jacksetter	3.2	10.0	–	5.6	12.9	–	8.6	16.5	–
Longwall Tailgate Operator	4.3	11.3	–	5.8	13.2	–	8.2	16.1	–
Mechanic and Helper	1.7	8.1	84.6	5.3	12.5	97.9	–	–	–
Mobile Bridge Operator	2.3	8.9	87.1	4.6	11.7	95.7	5.0	12.2	97.0
Roof Bolter	2.2	8.7	86.5	4.5	11.5	95.1	6.6	14.2	102.9
Scoop Car Operator	2.3	8.9	–	6.3	13.8	–	9.7	18.0	–
Section Foreman	2.0	8.4	85.8	9.4	17.6	112.7	19.5	30.0	146.8
Shuttle Car Operator	1.8	8.3	85.2	4.8	12.0	96.3	7.8	15.6	107.1
Uni-Hauler Operator	1.6	8.0	84.4	6.7	14.2	103.0	–	–	–
Utility Man	2.3	8.8	–	7.1	14.8	–	–	–	–
All Other Underground Jobs	2.5	9.1	87.6	7.3	15.0	105.2	17.9	28.0	141.5
Part 90 Miners	0.5	6.6	–	2.0	8.5	–	3.4	10.2	–

Table A.5. Estimated Excess Risk of NMRD Mortality by Age 85 After 45 Years of Occupational Exposure at Baseline Exposure Levels (per 1,000 Workers)

	Low-Recurrence			Mid-Recurrence			High-Recurrence		
Occupation	Low-/Med.-Rank	High-Rank Bituminous	Anthracite	Low-/Med.-Rank	High-Rank Bituminous	Anthracite	Low-/Med.-Rank	High-Rank Bituminous	Anthracite
Auger Operator	9.1	25.5	–	11.4	28.4	–	23.2	42.7	–
Continuous Miner Operator	7.3	23.4	200.2	11.6	28.6	213.3	16.5	34.5	227.7
Cutting Machine Operator	8.0	24.2	–	13.0	30.3	–	18.9	37.4	–
Drill Operator	6.7	22.7	–	15.4	33.1	–	–	–	–
Electrician and Helper	4.8	20.3	192.1	11.2	28.1	211.9	–	–	–
Laborer	5.8	21.5	195.4	23.1	42.5	246.2	27.8	48.2	258.9
Loading Machine Operator	4.4	19.8	–	–	–	–	–	–	–
Longwall Headgate Operator	9.0	25.4	–	13.5	30.9	–	20.0	38.8	–
Longwall Jacksetter	9.7	26.2	–	15.5	33.3	–	22.7	42.0	–
Longwall Tailgate Operator	12.1	29.2	–	16.0	33.9	–	21.8	40.9	–
Mechanic and Helper	5.8	21.5	195.3	14.6	32.3	222.2	–	–	–
Mobile Bridge Operator	7.4	23.4	200.3	13.1	30.4	217.8	14.0	31.5	220.4
Roof Bolter	7.0	23.0	199.2	12.7	29.9	216.5	18.0	36.3	232.0
Scoop Car Operator	7.4	23.5	–	17.2	35.3	–	25.5	45.5	–
Section Foreman	6.5	22.4	197.6	24.7	44.5	250.8	49.2	73.9	310.1
Shuttle Car Operator	6.1	21.9	196.4	13.5	30.9	219.0	20.9	39.8	240.1
Uni-Hauler Operator	5.6	21.3	194.8	18.1	36.4	232.2	–	–	–
Utility Man	7.3	23.3	–	19.2	37.7	–	–	–	–
All Other Underground Jobs	7.7	23.9	201.4	19.6	38.3	236.6	45.2	69.2	301.6
Part 90 Miners	2.8	17.9	–	6.6	22.5	–	10.0	26.6	–

Tables A.6–A.10 correspond to the preceding tables and report estimates of excess risk of CWP, COPD, and death due to NMRD for each risk group *at reduced exposure levels after the adoption of CPDMs*. The estimates in these tables can be subtracted from the baseline levels in Tables A.1–A.5 to calculate the impact of CPDMs on the excess risk of respiratory disease due to coal mine dust.

Table A.6. Estimated Excess Risk of CWP by Age 73 After 45 Years of Occupational Exposure at Reduced Exposure Levels at Low/Medium Rank Bituminous Coal Mines (per 1,000 Workers)

	Low-Recurrence			Mid-Recurrence			High-Recurrence		
Occupation	CWP 1+	CWP 2+	PMF	CWP 1+	CWP 2+	PMF	CWP 1+	CWP 2+	PMF
Auger Operator	54.9	31.0	15.9	70.6	40.4	20.6	155.8	95.5	47.6
Continuous Miner Operator	43.5	24.3	12.5	72.1	41.3	21.0	106.2	62.5	31.5
Cutting Machine Operator	47.9	26.9	13.8	81.6	47.1	23.9	123.3	73.6	36.9
Drill Operator	39.6	22.1	11.4	98.1	57.4	29.0	–	–	–
Electrician and Helper	27.1	15.0	7.8	68.9	39.3	20.1	–	–	–
Laborer	33.8	18.7	9.7	154.6	94.7	47.2	190.2	119.8	59.4
Loading Machine Operator	25.1	13.8	7.2	–	–	–	–	–	–
Longwall Headgate Operator	54.1	30.5	15.7	85.0	49.2	25.0	132.0	79.4	39.7
Longwall Jacksetter	58.8	33.3	17.0	98.7	57.8	29.2	151.8	92.7	46.2
Longwall Tailgate Operator	75.5	43.4	22.1	102.4	60.1	30.3	145.0	88.1	44.0
Mechanic and Helper	33.4	18.5	9.6	92.9	54.1	27.4	–	–	–
Mobile Bridge Operator	43.7	24.5	12.6	82.3	47.5	24.1	88.5	51.4	26.0
Roof Bolter	41.4	23.1	11.9	79.4	45.8	23.3	117.0	69.5	34.9
Scoop Car Operator	44.0	24.6	12.7	111.1	65.7	33.1	173.3	107.7	53.5
Section Foreman	38.2	21.2	11.0	167.3	103.5	51.4	351.1	251.6	125.0
Shuttle Car Operator	35.8	19.9	10.3	85.2	49.3	25.0	138.1	83.5	41.7
Uni-Hauler Operator	32.4	18.0	9.3	117.6	69.9	35.1	–	–	–
Utility Man	43.0	24.1	12.4	125.5	75.1	37.6	–	–	–
All Other Underground Jobs	46.0	25.8	13.3	128.8	77.2	38.7	322.6	226.0	111.8
Part 90 Miners	15.4	8.4	4.4	38.9	21.7	11.2	61.1	34.7	17.7

Table A.7. Estimated Excess Risk of CWP by Age 73 After 45 Years of Occupational Exposure at Reduced Exposure Levels at High Rank Bituminous or Anthracite Coal Mines (per 1,000 Workers)

	Low-Recurrence			Mid-Recurrence			High-Recurrence		
Occupation	**CWP 1+**	**CWP 2+**	**PMF**	**CWP 1+**	**CWP 2+**	**PMF**	**CWP 1+**	**CWP 2+**	**PMF**
Auger Operator	95.5	68.9	45.9	124.9	93.3	62.8	288.5	255.1	183.8
Continuous Miner Operator	74.5	52.3	34.7	127.6	95.7	64.5	193.1	155.7	107.5
Cutting Machine Operator	82.6	58.6	38.9	145.8	111.7	75.7	226.2	188.7	132.1
Drill Operator	67.5	47.0	31.1	177.5	140.8	96.6	–	–	–
Electrician and Helper	45.5	30.7	20.2	121.6	90.6	60.9	–	–	–
Laborer	57.1	39.2	25.8	286.3	252.6	181.8	352.8	329.2	245.0
Loading Machine Operator	41.9	28.2	18.5	–	–	–	–	–	–
Longwall Headgate Operator	94.1	67.7	45.1	152.3	117.5	79.9	242.9	205.9	145.2
Longwall Jacksetter	102.7	74.7	49.9	178.7	141.9	97.4	280.9	246.7	177.1
Longwall Tailgate Operator	134.2	101.4	68.5	185.7	148.6	102.3	268.0	232.6	165.9
Mechanic and Helper	56.5	38.8	25.5	167.4	131.4	89.8	–	–	–
Mobile Bridge Operator	75.0	52.7	34.9	147.1	112.8	76.5	158.9	123.5	84.2
Roof Bolter	70.7	49.4	32.7	141.6	108.0	73.1	214.0	176.3	122.8
Scoop Car Operator	75.5	53.1	35.1	202.6	165.0	114.4	321.6	292.5	214.2
Section Foreman	65.0	45.1	29.7	310.3	279.6	203.5	602.9	650.8	566.1
Shuttle Car Operator	60.7	41.9	27.6	152.6	117.8	80.1	254.8	218.4	154.9
Uni-Hauler Operator	54.8	37.5	24.7	215.2	177.5	123.7	–	–	–
Utility Man	73.7	51.7	34.2	230.5	193.0	135.4	–	–	–
All Other Underground Jobs	79.2	56.0	37.1	236.7	199.5	140.3	565.8	601.8	510.4
Part 90 Miners	25.3	16.6	10.8	66.3	46.1	30.4	107.0	78.3	52.4

Table A.8. Estimated Excess Risk of COPD by Age 73 After 45 Years of Occupational Exposure at Reduced Exposure Levels (per 1,000 Workers)

Occupation	Low-Recurrence	Mid-Recurrence	High-Recurrence
Auger Operator	35.1	44.6	94.3
Continuous Miner Operator	28.0	45.5	65.7
Cutting Machine Operator	30.7	51.2	75.7
Drill Operator	25.6	61.0	–
Electrician and Helper	17.7	43.5	–
Laborer	21.9	93.6	113.9
Loading Machine Operator	16.4	–	–
Longwall Headgate Operator	34.6	53.2	80.6
Longwall Jacksetter	37.4	61.3	92.0
Longwall Tailgate Operator	47.5	63.5	88.2
Mechanic and Helper	21.7	57.9	–
Mobile Bridge Operator	28.1	51.6	55.3
Roof Bolter	26.7	49.9	72.0
Scoop Car Operator	28.3	68.6	104.3
Section Foreman	24.7	100.9	206.7
Shuttle Car Operator	23.2	53.3	84.2
Uni-Hauler Operator	21.1	72.4	–
Utility Man	27.7	76.9	–
All Other Underground Jobs	29.6	78.8	189.8
Part 90 Miners	10.1	25.1	38.8

Table A.9. Estimated Excess Risk of NMRD Mortality by Age 73 After 45 Years of Occupational Exposure at Reduced Exposure Levels (per 1,000 Workers)

	Low-Recurrence			Mid-Recurrence			High-Recurrence		
Occupation	**Low-/Med.-Rank**	**High-Rank Bituminous**	**Anthracite**	**Low-/Med.-Rank**	**High-Rank Bituminous**	**Anthracite**	**Low-/Med.-Rank**	**High-Rank Bituminous**	**Anthracite**
Auger Operator	2.8	9.5	–	3.7	10.6	–	8.2	16.1	–
Continuous Miner Operator	2.1	8.7	86.4	3.8	10.7	92.5	5.6	12.9	99.2
Cutting Machine Operator	2.4	9.0	–	4.3	11.3	–	6.5	14.1	–
Drill Operator	1.9	8.4	–	5.2	12.4	–	–	–	–
Electrician and Helper	1.1	7.4	82.7	3.6	10.5	91.8	–	–	–
Laborer	1.6	7.9	84.2	8.1	16.0	108.2	9.9	18.2	114.6
Loading Machine Operator	1.0	7.3	–	–	–	–	–	–	–
Longwall Headgate Operator	2.8	9.4	–	4.5	11.5	–	7.0	14.6	–
Longwall Jacksetter	3.0	9.7	–	5.2	12.5	–	8.0	15.9	–
Longwall Tailgate Operator	4.0	10.9	–	5.4	12.7	–	7.6	15.4	–
Mechanic and Helper	1.5	7.9	84.2	4.9	12.1	96.7	–	–	–
Mobile Bridge Operator	2.1	8.7	86.5	4.3	11.4	94.6	4.7	11.8	95.8
Roof Bolter	2.0	8.5	85.9	4.2	11.2	94.0	6.2	13.6	101.3
Scoop Car Operator	2.2	8.7	–	5.9	13.3	–	9.1	17.2	–
Section Foreman	1.8	8.3	85.2	8.8	16.8	110.5	18.1	28.3	142.3
Shuttle Car Operator	1.7	8.1	84.7	4.5	11.6	95.1	7.3	15.0	105.2
Uni-Hauler Operator	1.5	7.8	83.9	6.2	13.7	101.4	–	–	–
Utility Man	2.1	8.6	–	6.6	14.2	–	–	–	–
All Other Underground Jobs	2.3	8.8	87.0	6.8	14.4	103.5	16.6	26.4	137.3
Part 90 Miners	0.4	6.5	–	1.9	8.3	–	3.2	9.9	–

Table A.10. Estimated Excess Risk of NMRD Mortality by Age 85 After 45 Years of Occupational Exposure at Reduced Exposure Levels (per 1,000 Workers)

	Low-Recurrence			Mid-Recurrence			High-Recurrence		
Occupation	Low-/Med.-Rank	High-Rank Bituminous	Anthracite	Low-/Med.-Rank	High-Rank Bituminous	Anthracite	Low-/Med.-Rank	High-Rank Bituminous	Anthracite
Auger Operator	8.6	24.9	–	10.8	27.6	–	21.8	40.9	–
Continuous Miner Operator	6.9	22.9	198.9	11.0	27.8	211.3	15.5	33.3	224.8
Cutting Machine Operator	7.6	23.7	–	12.3	29.4	–	17.7	36.0	–
Drill Operator	6.4	22.2	–	14.5	32.1	–	–	–	–
Electrician and Helper	4.5	19.9	191.3	10.5	27.3	210.0	–	–	–
Laborer	5.5	21.2	194.5	21.6	40.8	242.3	26.0	46.1	254.3
Loading Machine Operator	4.2	19.6	–	–	–	–	–	–	–
Longwall Headgate Operator	8.5	24.8	–	12.7	29.9	–	18.8	37.3	–
Longwall Jacksetter	9.1	25.6	–	14.5	32.2	–	21.3	40.3	–
Longwall Tailgate Operator	11.4	28.4	–	15.0	32.7	–	20.5	39.3	–
Mechanic and Helper	5.5	21.1	194.3	13.8	31.2	219.7	–	–	–
Mobile Bridge Operator	7.0	22.9	199.0	12.4	29.5	215.5	13.2	30.5	218.0
Roof Bolter	6.6	22.5	198.0	12.0	29.0	214.3	16.9	35.0	228.9
Scoop Car Operator	7.0	23.0	–	16.2	34.1	–	24.0	43.6	–
Section Foreman	6.2	22.0	196.5	23.2	42.7	246.7	45.8	69.9	302.8
Shuttle Car Operator	5.8	21.5	195.4	12.8	30.0	216.6	19.6	38.3	236.6
Uni-Hauler Operator	5.3	20.9	193.8	17.0	35.1	229.1	–	–	–
Utility Man	6.9	22.8	–	18.0	36.4	–	–	–	–
All Other Underground Jobs	7.3	23.4	200.1	18.4	36.9	233.2	42.2	65.6	294.7
Part 90 Miners	2.7	17.7	–	6.3	22.1	–	9.5	26.0	–

Estimating Benefits over Time

Step 5 of the analysis in Chapter 2 describes our assumptions about the timing of future benefits. Our analysis estimates a stream of benefits over a 65-year time horizon assuming an average job tenure of 45 years and latency period of approximately 20 years associated with the respiratory diseases in this study. Table A.11 shows the timing of benefits associated with risk reductions for each category of disease by age 73 based on a cumulative Poisson distribution with a mean of 20 years and an additional one-year lag to account for reduced levels of exposure during the first year, which results in the risk reduction. We note that the monetized benefits in the case study are sensitive to the choice of the time horizon, the probability distribution, and the discount rate in the analysis.

Table A.11. Estimated Benefits over Time by Age 73, by Year

Year	Percentage of Steady State Benefits Realized	Number of Fatal and Nonfatal Cases Avoided per Year				
		CWP 1+	CWP 2+	PMF	COPD	NMRD
1	0.0%	0.0	0.0	0.0	0.0	0.0
2	0.0%	0.0	0.0	0.0	0.0	0.0
3	0.0%	0.0	0.0	0.0	0.0	0.0
4	0.0%	0.0	0.0	0.0	0.0	0.0
5	0.0%	0.0	0.0	0.0	0.0	0.0
6	0.0%	0.0	0.0	0.0	0.0	0.0
7	0.0%	0.0	0.0	0.0	0.0	0.0
8	0.1%	0.0	0.0	0.0	0.0	0.0
9	0.2%	0.0	0.0	0.0	0.0	0.0
10	0.5%	0.0	0.0	0.0	0.0	0.0
11	1.1%	0.1	0.0	0.0	0.0	0.0
12	2.1%	0.1	0.1	0.1	0.0	0.0
13	3.9%	0.2	0.2	0.1	0.1	0.0
14	6.6%	0.3	0.3	0.2	0.1	0.0
15	10.5%	0.5	0.4	0.3	0.2	0.0
16	15.7%	0.8	0.6	0.4	0.3	0.0
17	22.1%	1.1	0.9	0.6	0.4	0.0
18	29.7%	1.4	1.2	0.8	0.6	0.1
19	38.1%	1.8	1.5	1.1	0.7	0.1
20	47.0%	2.3	1.9	1.3	0.9	0.1
21	55.9%	2.7	2.3	1.6	1.1	0.1
22	64.4%	3.1	2.6	1.8	1.2	0.1
23	72.1%	3.5	2.9	2.1	1.4	0.2
24	78.7%	3.8	3.2	2.2	1.5	0.2
25	84.3%	4.1	3.4	2.4	1.6	0.2
26	88.8%	4.3	3.6	2.5	1.7	0.2
27	92.2%	4.5	3.7	2.6	1.8	0.2
28	94.8%	4.6	3.8	2.7	1.8	0.2
29	96.6%	4.7	3.9	2.8	1.9	0.2

Year	Percentage of Steady State Benefits Realized	Number of Fatal and Nonfatal Cases Avoided per Year				
		CWP 1+	CWP 2+	PMF	COPD	NMRD
30	97.8%	4.7	4.0	2.8	1.9	0.2
31	98.7%	4.8	4.0	2.8	1.9	0.2
32	99.2%	4.8	4.0	2.8	1.9	0.2
33	99.5%	4.8	4.0	2.8	1.9	0.2
34	99.7%	4.8	4.0	2.8	1.9	0.2
35	99.9%	4.8	4.0	2.9	1.9	0.2
36	99.9%	4.8	4.0	2.9	1.9	0.2
37	100.0%	4.8	4.0	2.9	1.9	0.2
38	100.0%	4.8	4.0	2.9	1.9	0.2
39	100.0%	4.8	4.0	2.9	1.9	0.2
40	100.0%	4.8	4.0	2.9	1.9	0.2
41	100.0%	4.8	4.0	2.9	1.9	0.2
42	100.0%	4.8	4.0	2.9	1.9	0.2
43	100.0%	4.8	4.0	2.9	1.9	0.2
44	100.0%	4.8	4.0	2.9	1.9	0.2
45	100.0%	4.8	4.0	2.9	1.9	0.2
46	100.0%	4.8	4.0	2.9	1.9	0.2
47	100.0%	4.8	4.0	2.9	1.9	0.2
48	100.0%	4.8	4.0	2.9	1.9	0.2
49	100.0%	4.8	4.0	2.9	1.9	0.2
50	100.0%	4.8	4.0	2.9	1.9	0.2
51	100.0%	4.8	4.0	2.9	1.9	0.2
52	100.0%	4.8	4.0	2.9	1.9	0.2
53	100.0%	4.8	4.0	2.9	1.9	0.2
54	100.0%	4.8	4.0	2.9	1.9	0.2
55	100.0%	4.8	4.0	2.9	1.9	0.2
56	100.0%	4.8	4.0	2.9	1.9	0.2
57	100.0%	4.8	4.0	2.9	1.9	0.2
58	100.0%	4.8	4.0	2.9	1.9	0.2
59	100.0%	4.8	4.0	2.9	1.9	0.2
60	100.0%	4.8	4.0	2.9	1.9	0.2
61	100.0%	4.8	4.0	2.9	1.9	0.2
62	100.0%	4.8	4.0	2.9	1.9	0.2
63	100.0%	4.8	4.0	2.9	1.9	0.2
64	100.0%	4.8	4.0	2.9	1.9	0.2
65	100.0%	4.8	4.0	2.9	1.9	0.2
Total		**218**	**182**	**128**	**87**	**10**

NOTE: Totals may not sum precisely due to rounding.

References

Arias, Elizabeth, Jiaquan Xu, and Kenneth D. Kochanek, "United States Life Tables, 2016," *National Vital Statistics Reports*, Vol. 68, No. 4. Hyattsville, Md.: National Center for Health Statistics, 2019.

Attfield, M. D., and E. D. Kuempel, "Mortality Among U.S. Underground Coal Miners, a 23-Year Follow-Up," *American Journal of Industrial Medicine*, Vol. 51, No. 4, 2008, pp. 231–245.

Attfield, M. D., and N. S. Seixas, "Prevalence of Pneumoconiosis and Its Relationship to Dust Exposure in a Cohort of U.S. Bituminous Coal Miners and Ex-Miners," *American Journal of Industrial Medicine*, Vol. 27, No. 1, 1995, pp. 137–151.

Avery, Larry, Allie Jacobs, Jennifer Moore, Carlotta Boone, Jennifer Marshall, Allison Barnard Feeney, Y. Tina Lee, Deogratias Kibira, and Tom Malone, *Ambulance Patient Compartment Human Factors Design Guidebook*, Washington, D.C.: Department of Homeland Security, 2015.

Bellemare, Marc F., and Casey J. Wichman, "Elasticities and the Inverse Hyperbolic Sine Transformation," February 24, 2019. As of July 13, 2019: http://marcfbellemare.com/wordpress/wp-content/uploads/2019/02/BellemareWichmanIHSFebruary2019.pdf

Berkes, Howard, Huo Jingnan, Robert Benincasa, "An Epidemic Is Killing Thousands of Coal Miners. Regulators Could Have Stopped It," NPR/*Frontline*, December 18, 2018. As of July 10, 2019: https://www.npr.org/2018/12/18/675253856/an-epidemic-is-killing-thousands-of-coal-miners-regulators-could-have-stopped-it

Berkowitz, Deborah, "OSHA Enforcement Activity Declines Under the Trump Administration," National Employment Law Project Data Brief, June 11, 2018. As of July 13, 2019: https://www.nelp.org/publication/osha-enforcement-activity-declines-trump-administration/

Blackburn, M. L., "The Relative Performance of Poisson and Negative Binomial Regression Estimators," *Oxford Bulletin of Economics and Statistics*, Vol. 77, No. 4, 2014, pp. 605–616.

Blackley, David J., Cara N. Halldin, and A. Scott Laney, "Continued Increase in Prevalence of Coal Workers' Pneumoconiosis in the United States, 1970–2017," *American Journal of Public Health*, Vol. 108, No. 9, 2018, pp. 1220–1222.

BLS—*See* Bureau of Labor Statistics.

Bureau of Labor Statistics, “Nonfatal Cases Involving Days Away from Work: Selected Characteristics (2003–2010),” webpage, undated-a. As of November 5, 2019: https://data.bls.gov/cgi-bin/dsrv?ch

———, “Nonfatal Cases Involving Days Away from Work: Selected Characteristics (2011 Forward),” webpage, undated-b. As of November 5, 2019: https://data.bls.gov/cgi-bin/dsrv?cs

———, “Occupational Injuries/Illnesses and Fatal Injuries Profiles,” webpage, undated-c. As of November 5, 2019: https://data.bls.gov/gqt/InitialPage

———, “Occupational Employment Statistics,” webpage, May 2018. As of November 5, 2019: https://www.bls.gov/oes/tables.htm

———, “Labor Force Statistics from the Current Population Survey,” webpage, last updated January 18, 2019a. As of July 4, 2019a: https://www.bls.gov/cps/cpsaat08.htm

———, “Occupational Employment Statistics—OES Research Estimates by State and Industry,” webpage, last updated March 29, 2019b. As of November 5, 2019: https://www.bls.gov/oes/current/oes_research_estimates.htm

———, “Injuries, Illnesses, and Fatalities,” webpage, last updated April 5, 2019c. As of November 5, 2019: https://www.bls.gov/iif/soii-bibliography.htm

CAAS GVS—*See* Commission on Accreditation of Ambulance Services’ Ground Vehicle Standard for Ambulances.

Cameron, A. C., and P. K. Trivedi, *Regression Analysis of Count Data*, 2nd ed., Cambridge: Cambridge University Press, 2013.

Cantrell, B. K., K. L. Williams, S. W. Stein, D. Hassel, and H. Patashnick, “Continuous Respirable Mine Dust Monitor Development,” *Proceedings of the 27th Annual Institute on Mining Health, Safety and Research, Blacksburg, Virginia, August 26–28, 1996*, Blacksburg, Va.: Virginia Polytechnic Institute and State University, pp. 91–102. As of January 17, 2019: https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/crmd.pdf

Colinet, Jay F., James P. Rider, Jeffrey M. Listak, John A. Organiscak, and Anita L. Wolfe, “Best Practices for Dust Control in Coal Mining,” NIOSH Information Circular 9517, January 2010. As of November 5, 2019: https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/2010-110.pdf

Commission on Accreditation of Ambulance Services' Ground Vehicle Standard for Ambulances, "CAAS GVS V2.0," webpage, June 17, 2019. As of November 5, 2019: http://www.groundvehiclestandard.org/sdm_downloads/caas-gvs-v2-0/

Council of State and Territorial Epidemiologists, Occupational Health Surveillance Subcommittee, "Guidance: Public Health Referrals to OSHA," September 2011. As of July 15, 2019: http://www.cste2.org/webpdfs/occupational/OSHAreferral922011.pdf

Cromartie, John, and Dennis Vilorio, "Rural Population Trends," *Amber Waves*, February 15, 2019. As of July 24, 2019: https://www.ers.usda.gov/amber-waves/2019/february/rural-population-trends/

Cummings, Peter, James D. Wells, and Frederick P. Rivara, "Estimating Seat Belt Effectiveness Using Matched-Pair Cohort Methods," *Accident Analysis and Prevention*, Vol. 35, no. 1, 2003, pp. 143–149.

Current, Richard S., Paul H. Moore, James D. Green, John R. Yannaccone, Gary R. Whitman, and Larry A. Sicher, "Crash Testing of Ambulance Chassis Cab Vehicles," *SAE Transactions*, 2007, pp. 316–334.

Davis, Letitia K., Kathleen M. Grattan, Sangwoo Tak, Lucy F. Bullock, Al Ozonoff, and Leslie I. Boden, "Use of Multiple Data Sources for Surveillance of Work-Related Amputations in Massachusetts: Comparison with Official Estimates and Implications for National Surveillance," *American Journal of Industrial Medicine*, Vol. 57, 2014, pp. 1120–1132.

Department of Labor, "Division of Coal Mine Workers' Compensation (DCMWC): Black Lung Program Statistics," webpage, undated. As of September 24, 2019: https://www.dol.gov/owcp/dcmwc/statistics/TotalBenefitsPayment.htm

Dixon, Jennifer, "National Group Blasts MIOSHA, Asks for Review," *Detroit Free Press*, May 3, 2019. As of July 4, 2019: https://www.freep.com/story/news/local/2019/05/03/group-wants-miosha-review-nessel/3644104002/

Elliott, Graham, Thomas J. Rothenberg, and James H. Stock, "Efficient Tests for an Autoregressive Unit Root," *Econometrica*, Vol. 64, 1996, pp. 813–836.

Elvik, Rune, Alena Høye, Truls Vaa, and Michael Sørensen, "Vehicle Design and Protective Devices," in *The Handbook of Road Safety Measures*, Emerald Group Publishing Limited, 2009.

Emergency Medical Services, "NHTSA Advances Ground Ambulance Safety by Tracking and Investigating Crashes," webpage, March–April 2015. As of November 5, 2019: https://www.ems.gov/newsletter/marapr2015/ground-ambulance-safety.html

EMS—*See* Emergency Medical Services.

Energy Information Administration, *Annual Coal Report 2017*, Washington, D.C.: U.S. Department of Energy, November 2018. As of December 6, 2019: https://www.eia.gov/coal/annual/archive/05842017.pdf

Environmental Protection Agency, *Health and Welfare Benefits Analyses to Support the Second Section 812 Benefit-Cost Analysis of the Clean Air Act, Final Report*, prepared by Industrial Economics, Inc., February 2011a. As of November 5, 2019: https://www.epa.gov/sites/production/files/2015-07/documents/benefitsfullreport.pdf

———, *Regulatory Impact Analysis for the Federal Implementation Plans to Reduce Interstate Transport of Fine Particulate Matter and Ozone in 27 States; Correction of SIP Approvals for 22 States*, June 2011b. As of November 5, 2019: https://www3.epa.gov/ttn/ecas/docs/ria/transport_ria_final-csapr_2011-06.pdf

EPA—*See* Environmental Protection Agency.

Federal Transit Administration, "2001 Table 24: Number of Injuries–Collisions and Non-Collisions," webpage, 2001. As of November 5, 2019: https://www.transit.dot.gov/ntd/data-product/2001-table-24-number-injuries-collisions-and-non-collisions

Foley, Michael, Zihong Fan, Eddy Rauser, and Barbara Silverstein, "The Impact of Regulatory Enforcement and Consultation Visits on Workers' Compensation Claims Incidence Rates and Costs, 1999–2008," *American Journal of Industrial Medicine*, Vol. 55, 2012, pp. 976–990.

Food Safety and Inspection Service, *Risk Assessment of the Potential Human Health Effect of Applying Continuous Inspection to Catfish*, Washington, D.C.: Department of Agriculture, July 2012.

Friedman, Lee, Colin Krupczak, Sherry Brandt-Rauf, and Linda Forst, "Occupational Amputations in Illinois 2000–2007: BLS vs. Data Linkage of Trauma Registry, Hospital Discharge, Workers Compensation Databases and OSHA Citations," *Injury*, Vol. 44, 2013, pp. 667–673.

GAO—*See* Government Accountability Office.

General Services Administration, "Ambulances," webpage, last updated October 29, 2019. As of November 5, 2019: https://www.gsa.gov/buying-selling/products-services/transportation-logistics-services/gsa-fleet-vehicle-purchasing/vehicles-and-products/ambulances

Government Accountability Office, *Black Lung Benefits Program: Options for Improving Trust Fund Finances*, GAO-18-351, May 2018. As of November 5, 2019: https://www.gao.gov/assets/700/692103.pdf

Gray, W. B., and J. M. Mendeloff, "The Declining Effects of OSHA Inspections on Manufacturing Injuries, 1979–1998," *ILR Review*, Vol. 58, No. 4, 2005, pp. 571–587.

Green, J. D., J. R. Yannaccone, R. S. Current, L. A. Sicher, P. H. Moore, and G. R. Whitman, "Assessing the Performance of Various Restraints on Ambulance Patient Compartment Workers During Crash Events," *International Journal of Crashworthiness*, Vol. 15, No. 5, 2010, pp. 517–541.

Grosse, Scott D., Kurt V. Krueger, and Mercy Mvundura, "Economic Productivity by Age and Sex: 2007 Estimates for the United States," *Medical Care*, Vol. 47, No. 7 (Suppl. 1), 2009, pp. S94–103.

GSA—*See* General Services Administration.

Haas, E., and J. Colinet, "Miners Implement Corrective Actions in Response to CPDM Dust Data," *Coal Age*, Vol. 123, No. 2, 2018, pp. 36–38.

Hilleman, Daniel E., Naresh Dewan, Mark Malesker, and Mitchell Friedman, "Pharmacoeconomic Evaluation of COPD," *Chest*, Vol. 118, No. 5, 2000, pp. 1278–1285.

Injury Facts, "Workers' Compensation Costs," webpage, undated. As of September 2, 2019: https://injuryfacts.nsc.org/work/costs/workers-compensation-costs/

———, "Guide to Calculating Costs," 2017. As of July 24, 2019: https://injuryfacts.nsc.org/all-injuries/costs/guide-to-calculating-costs/data-details/

Johnson, Matthew S., "Regulation by Shaming: Deterrence Effects of Publicizing Violations of Workplace Safety and Health Laws," August 30, 2019. As of November 5, 2019: https://drive.google.com/file/d/1HcKpGXZuFWNNLa1YTl0A4Hte1BiJabT-/view

Kica, Joanna, and Kenneth D. Rosenman, "Multisource Surveillance System for Work-Related Burns," *Journal of Occupational and Environmental Medicine*, Vol. 54, No. 5, 2012, pp. 642–647.

———, "Surveillance for Work-Related Skull Fractures in Michigan," *Journal of Safety Research*, Vol. 51, 2014, pp. 49–56.

———, "Multi-Source Surveillance for Work-Related Crushing Injuries," *American Journal of Industrial Medicine*, Vol. 61, No. 2, 2018, pp. 148–156.

———, "Multisource Surveillance for Non-Fatal Work-Related Agricultural Injuries," *Journal of Agromedicine*, May 2019, pp. 1–10.

Kuempel, E. D., V. Vallyathan, and F. H. Y. Green, "Emphysema and Pulmonary Impairment in Coal Miners: Quantitative Relationship with Dust Exposure and Cigarette Smoking," Inhaled Particles X (September 23–25, 2008, Manchester, UK), *Journal of Physics: Conference Series*, No. 151, 2009.

Largo, Thomas W., and Kenneth D. Rosenman, "Surveillance of Work-Related Amputations in Michigan Using Multiple Data Sources: Results for 2006–2012," *Occupational and Environmental Medicine*, Vol. 72, No. 3, 2015, pp. 171–176.

Larmon, Baxter, Todd L. LeGassick, and David L. Schriger, "Differential Front and Back Seat Safety Belt Use by Prehospital Care Providers," *American Journal of Emergency Medicine*, Vol. 11, No. 6, 1993, pp. 595–599.

Leigh, J. Paul, "Economic Burden of Occupational Injury and Illness in the United States," *Milbank Quarterly*, Vol. 89, No. 4, 2011, pp. 728–772.

Levick, Nadine, Guohua Li, and John Yannaccone, "Biomechanics of the Patient Compartment of Ambulance Vehicles Under Crash Conditions: Testing Countermeasures to Mitigate Injury," *SAE Transactions*, 2001a, pp. 1329–1335.

———, "Development of a Dynamic Testing Procedure to Assess Crashworthiness of the Rear Patient Compartment of Ambulance Vehicles," SAE Technical Paper No. 2001-06-0053, 2001b.

Levine, David I., Michael W. Toffel, and Matthew S. Johnson, "Randomized Government Safety Inspections Reduce Worker Injuries with No Detectable Job Loss," *Science*, Vol. 336, No. 6083, May 18, 2012, pp. 907–911.

Li, Ling, and Perry Singleton, "The Effect of Workplace Inspections on Worker Safety," *ILR Review*, Vol. 72, No. 3, 2019, pp. 718–748.

Lindsley, William G., Tia L. McClelland, Dylan T. Neu, Stephen B. Martin Jr., Kenneth R. Mead, Robert E. Thewlis, and John D. Noti, "Ambulance Disinfection Using Ultraviolet Germicidal Irradiation (UVGI): Effects of Fixture Location and Surface Reflectivity," *Journal of Occupational and Environmental Hygiene*, Vol. 15, No. 1, 2018, pp. 1–12.

Magat, Wesley A., W. Kip Viscusi, and Joel Huber, "A Reference Lottery Metric for Valuing Health," *Management Science*, Vol. 42, No. 8, 1996, pp. 1118–1129.

Mazurek, Jacek M., John Wood, David J. Blackley, and David N. Weissman, "Coal Workers' Pneumoconiosis—Attributable Years of Potential Life Lost to Life Expectancy and Potential Life Lost Before Age 65 Years—United States, 1999–2016," *Morbidity and Mortality Weekly Report*, Vol. 67, No. 30, 2018, pp. 819–824.

McCall, Brian P., and Irwin B. Horwitz, "An Assessment and Quantification of the Rates, Costs, and Risk Factors of Occupational Amputations: Analysis of Kentucky Workers' Compensation Claims, 1994–2003," *American Journal of Industrial Medicine*, Vol. 49, 2006, pp. 1031–1038.

Mears, Greg, Beth Armstrong, Antonio R. Fernandez, N. Clay Mann, Kevin McGinnis, Cindy Raisor Mears, Nels D. Sanddal, Teri L. Sanddal, and Frances S. Shofer, *2011 National EMS Assessment*, 2012. As of November 5, 2019: https://www.ems.gov/pdf/2011/National_EMS_Assessment_Final_Draft_12202011.pdf

Michaels, David, "Memorandum for Regional Administrators: Enforcement Weighting System (EWS)," September 20, 2015. As of July 15, 2019: https://www.osha.gov/dep/enforcement/ews_memo_09302015.html

———, *Year One of OSHA's Severe Injury Reporting Program: An Impact Evaluation*, March 17, 2016. As of November 5, 2019: https://www.osha.gov/injuryreport/2015.pdf

Michigan State University, "Occupational and Environmental Medicine—Annual Reports," webpage, undated-a. As of November 5, 2019: https://oem.msu.edu/index.php/annual-reports

———, "Occupational and Environmental Medicine—Hazard Alerts," webpage, undated-b. As of November 5, 2019: https://oem.msu.edu/index.php/work-related-injuries/miface-hazard-alerts

Miller, Benjamin M., David Metz, Troy D. Smith, Jesse Lastunen, Eric Landree, and Christopher Nelson, *Understanding the Economic Benefit Associated with Research and Services at the National Institute for Occupational Safety and Health: An Approach and Three Case Studies*, Santa Monica, Calif.: RAND Corporation, RR-2256-NIOSH, 2017. As of November 5, 2019: https://www.rand.org/pubs/research_reports/RR2256.html

Miller, Brian, Laura MacCalman, and P. A. Hutchison, *Mortality over an Extended Follow-Up Period in Coal Workers Exposed to Respirable Dust and Quartz*, Research Report TM/07/06, Edinburgh, UK: Institute of Occupational Medicine, November 2007 (revised October 2009).

Mine Safety and Health Administration, "Mine Injury and Worktime Quarterly Statistics Coal Data," webpage, undated. As of December 5, 2019: https://arlweb.msha.gov/ACCINJ/ALLCOAL.HTM

———, *Review of the Program to Control Respirable Coal Mine Dust in the United States*, Report of the Coal Mine Respirable Dust Task Group, June 1992. As of November 5, 2019: https://arlweb.msha.gov/s&hinfo/blacklung/Reports/1992ReviewCoalMineDust.pdf

———, *Report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers*, Washington, D.C.: MSHA, October 1996.

———, "Verification of Underground Coal Mine Operators' Dust Control Plans and Compliance Sampling for Respirable Dust," *Federal Register*, Vol. 68, No. 44, March 6, 2003, pp. 10784–10884.

———, "Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors," *Federal Register*, Vol. 75, No. 201, October 19, 2010, pp. 64412–64506.

———, *Quantitative Risk Assessment in Support of the Final Respirable Coal Mine Dust Rule: Statistical Methods and Analysis*, December 2013. As of November 5, 2019: https://arlweb.msha.gov/endblacklung/docs/Quantitativeanalysis.pdf

———, *Regulatory Economic Analysis for Lowering Miners' Exposure to Respirable Coal Mine Dust Including Continuous Personal Dust Monitors: Final Rule*, March 2014a. As of November 5, 2019: https://arlweb.msha.gov/endblacklung/docs/REAFinalRule.pdf

———, "Lowering Miners' Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors," *Federal Register*, Vol. 79, No. 84, May 1, 2014b, pp. 24814–24994. As of November 5, 2019: https://www.govinfo.gov/content/pkg/FR-2014-05-01/pdf/2014-09084.pdf

———, "Search MSHA Data Sets," webpage, 2019a. As of March 4, 2019: https://arlweb.msha.gov/OpenGovernmentData/OGIMSHA.asp

———, "Respirable Silica (Quartz)," *Federal Register*, Vol. 84, No. 168, August 29, 2019b, pp. 45452–45456. As of September 30, 2019: https://www.govinfo.gov/content/pkg/FR-2019-08-29/pdf/2019-18478.pdf

Moran, Molly J., and Carlos Monje, "Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses: 2016 Adjustment," memorandum to secretarial officers and modal administrators, August 8, 2016. As of June 2019: https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20a%20Statistical%20Life%20Guidance.pdf

MSHA—*See* Mine Safety and Health Administration.

MSU—*See* Michigan State University.

National Academies of Sciences, Engineering, and Medicine, *A Smarter National Surveillance System for Occupational Safety and Health in the 21st Century*, Washington, D.C.: National Academies Press, 2018.

National Fire Protection Association, "NFPA 1917," webpage, 2019. As of November 5, 2019: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1917

National Highway Traffic Safety Administration, "Model Minimum Uniform Crash Criteria, 4th Edition Definitions," undated-a. As of November 5, 2019: https://safety.fhwa.dot.gov/hsip/spm/conversion_tbl/pdfs/kabco_definitions.pdf

———, "Seat Belts," webpage, undated-b. As of October 3, 2019: https://www.nhtsa.gov/risky-driving/seat-belts

———, *Final Regulatory Impact Analysis, Amendment to Federal Motor Vehicle Safety Standard 208, Passenger Car Front Seat Occupant Protection*, Publication No. DOT HS 806 572, Washington, D.C.: NHTSA, 1984.

———, *Fatality Reduction by Safety Belts for Front-Seat Occupants of Cars and Light Trucks*, Publication No. DOT HS 809 199, Washington, D.C.: NHTSA, 2000.

———, "The National Highway Traffic Safety Administration and Ground Ambulance Crashes," presentation, April 2014. As of November 5, 2019: https://www.ems.gov/pdf/GroundAmbulanceCrashesPresentation.pdf

National Institute for Occupational Safety and Health, *Criteria for a Recommended Standard: Occupational Exposure to Respirable Coal Mine Dust*, Publication No. 95-106, Washington, D.C: Department of Health and Human Services, September 1995.

———, "Machine-Mounted Continuous Respirable Dust Monitor," *Technology News*, No. 463, July 1997, pp. 1–2. As of January 17, 2019: https://www.cdc.gov/niosh/mining/works/coversheet74.html

———, *Performance of a New Personal Respirable Dust Monitor for Mine Use*, Publication No. 2004-151, Washington, D.C.: Department of Health and Human Services, 2004. As of January 17, 2019: https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/ri9663.pdf

———, *Laboratory and Field Performance of a Continuously Measuring Personal Respirable Dust Monitor*, Publication No. 2006-145, Report of Investigations 9669, Washington, D.C.: U.S. Department of Health and Human Services, 2006. As of January 17, 2019: https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/2006-145.pdf

———, *Work-Related Lung Disease Surveillance Report 2007*. Publication No. 2008143a, Washington, D.C.: U.S. Department of Health and Human Services, September 2008. As of November 5, 2019: https://www.cdc.gov/niosh/docs/2008-143/pdfs/2008-143.pdf?id=10.26616/NIOSHPUB2008143a

———, "National Survey of the Mining Population, Part 1: Employees," Information Circular 9527, June 2012a. As of October 18, 2018:
https://www.cdc.gov/niosh/mining/userfiles/works/pdfs/2012-152.pdf

———, "NIOSH Programs," webpage, last updated December 18, 2012b. As of November 5, 2019:
https://www.cdc.gov/niosh/programs.html

———, "Mining Facts—2015," webpage, 2015. As of March 4, 2019:
https://www.cdc.gov/niosh/mining/works/statistics/factsheets/miningfacts2015.html

———, "Improving EMS Worker Safety Through Ambulance Design and Testing," webpage, 2017a. As of November 5, 2019:
https://www.cdc.gov/niosh/topics/ems/videos.html

———, "Coal Workers' Pneumoconiosis: Mortality Data: Number of Deaths, Crude and Age-adjusted Death Rates, U.S. Residents Age 15 and Over, 1968–2014," May 2017b. As of May 9, 2019:
https://wwwn.cdc.gov/eworld/Grouping/Coal_Workers_Pneumoconiosis/93#Mortality%20Data

———, "Ambulance Crash Test Methods," *NIOSH Science Blog*, May 22, 2017c. As of November 5, 2019:
https://blogs.cdc.gov/niosh-science-blog/2017/05/22/ambulance-safety/

———, "State Surveillance Program," webpage, last updated January 3, 2018a. As of November 5, 2019:
https://www.cdc.gov/niosh/oep/statesurv.html#program

———, "About NIOSH," webpage, last updated March 28, 2018b. As of November 5, 2019:
https://www.cdc.gov/niosh/about/default.html

———, *Enhanced Coal Workers' Health Surveillance Program*, Publication Number 2019-112, Washington, D.C.: Department of Health and Human Services, October 2018c.

———, "The Work-Related Injury Statistics Query System," webpage, last updated September 23, 2019a. As of November 5, 2019:
https://wwwn.cdc.gov/wisards/workrisqs/

———, "Emergency Medical Services Workers," webpage, last updated September 16, 2019b. As of November 5, 2019:
https://www.cdc.gov/niosh/topics/ems/default.html

———, "Emergency Medical Services Workers—Injury Data," webpage, last updated September 16, 2019c. As of November 5, 2019:
https://www.cdc.gov/niosh/topics/ems/data.html

NFPA—*See* National Fire Protection Association.

Ng, Serena, and Pierre Perron, "Lag Length Selection and the Construction of Unit Root Tests with Good Size and Power," *Econometrica*, Vol. 69, 2001, pp. 1519–1554.

NHTSA—*See* National Highway Traffic Safety Administration.

NIOSH—*See* National Institute for Occupational Safety and Health.

Occupational Safety and Health Administration, "About OSHA," webpage, undated-a. As of July 4, 2019:
https://www.osha.gov/about.html

———, "Commonly Used Statistics," webpage, undated-b. As of July 4, 2019:
https://www.osha.gov/oshstats/commonstats.html

———, "Federal Annual Monitoring and Evaluation (FAME) Reports," webpage, undated-c. As of July 4, 2019:
https://www.osha.gov/stateplans/famereport

———, "State Plans," webpage, undated-d. As of July 4, 2019:
https://www.osha.gov/stateplans/

———, "Occupational Injury and Illness Recording and Reporting Requirements—NAICS Update and Reporting Revisions," *Federal Register*, September 18, 2014. As of November 5, 2019:
https://www.federalregister.gov/documents/2014/09/18/2014-21514/occupational-injury-and-illness-recording-and-reporting-requirements-naics-update-and-reporting

———, "Inspection Detail," webpage, May 27, 2015. As of November 5:
https://www.osha.gov/pls/imis/establishment.inspection_detail?id=1012118.015

———, "OSHA Instruction: Field Operations Manual (FOM)," 2016. As of July 13, 2019:
https://www.osha.gov/OshDoc/Directive_pdf/CPL_02-00-160.pdf

———, "Benefits of the OSHA On-Site Consultation Program: An Economic Analysis," working paper, August 1, 2018. As of July 15, 2019:
https://www.osha.gov/sites/default/files/2018_Benefits_OSHA_On-Site_Consultation_Program_Economic_Analysis.pdf

———, "Inspections Within Industry," webpage, November 4, 2019. As of November 7, 2019:
https://www.osha.gov/pls/imis/industry.html

OSHA—*See* Occupational Safety and Health Administration.

Page, Steven J., Jon C. Volkwein, Robert P. Vinson, Gerald J. Joy, Steven E. Mischler, Donald P. Tuchman, and Linda J. McWilliams, "Equivalency of a Personal Dust Monitor to the Current United States Coal Mine Respirable Dust Sampler," *Journal of Environmental Monitoring*, Vol. 10, No. 1, 2008, pp. 96–101.

Proudfoot, Steven, Paul Moore, and Roger Levine, "Safety in Numbers: A Survey on Ambulance Patient Compartment Safety," *Journal of Emergency Medical Services*, Vol. 32, No. 3, 2007, pp. 86–90.

Reynolds, Laura, Cara N. Halldin, A. Scott Laney, and David J. Blackley, "Coal Miner Participation in a Job Transfer Program Designed to Prevent Progression of Pneumoconiosis, United States, 1986–2016," *Archives of Environmental and Occupational Health*, Vol. 73, No. 6, 2018, pp. 344–346.

Rice, Dorothy P. ,Thomas A. Hodgson, and Andrea N. Kopstein, "The Economic Costs of Illness: A Replication and Update," *Health Care Financing Review*, Vol. 7, No. 1, 1985, pp. 61–80.

Road Safety Observatory, "Seat Belts," webpage, last updated January 12, 2018. As of November 5, 2019: https://www.roadsafetyobservatory.com/HowEffective/vehicles/seat-belts

Robertson, Leon S., "Estimates of Motor Vehicle Seat Belt Effectiveness and Use: Implications for Occupant Crash Protection," *American Journal of Public Health*, Vol. 66, No. 9, 1976, pp. 859–864.

Rosenman, Kenneth D. "Work-Related Amputations: Who's Counting?," *NIOSH Science Blog*, March 21, 2013. As of September 2, 2019: https://blogs.cdc.gov/niosh-science-blog/2013/03/21/amputations/

Rosenman, Kenneth D., Alice Kalush, Mary Jo Reilly, Joseph C. Gardiner, Mathew Reeves, and Zhewui Luo, "How Much Work-Related Injury and Illness Is Missed by the Current National Surveillance System?," *Journal of Occupational and Environmental Medicine*, Vol. 48, No. 4, 2006, pp. 357–365.

Santos Silva, J. M. C., and S. Tenreyro, "The Log of Gravity," *Review of Economics and Statistics*, Vol. 88, No. 4, 2006, pp. 641–658.

Schlick, D. P., and R. G. Peluso, "Respirable Dust Sampling Requirements Under the Federal Coal Mine Health and Safety Act of 1969," U.S. Bureau of Mines Information Circular 8484, 1970.

Smith, Noah, "A National Perspective on Ambulance Crashes and Safety: Guidance from the National Highway Traffic Safety Administration on Ambulance Safety for Patients and Providers," *EMS World*, Vol. 44, No. 9, 2015, pp. 91–92. As of November 5, 2019: https://www.ems.gov/pdf/emsworldambulancecrasharticlessept2015.pdf

Spieler, Emily A., and Gregory R. Wagner, "Counting Matters: Implications of Undercounting in the BLS Survey of Occupational Injuries and Illnesses," *American Journal of Industrial Medicine*, Vol. 57, 2014, 1077–1084.

Stanbury, Martha, Mary Jo Reilly, and Kenneth D. Rosenman, "Work-Related Amputations in Michigan, 1997," *American Journal of Industrial Medicine*, Vol. 44, No. 4, 2003, pp. 359–367.

Szymendera, Scott D., and Molly F. Sherlock, *The Black Lung Program, the Black Lung Disability Trust Fund, and the Excise Tax on Coal: Background and Policy Options*, Congressional Research Service Report 45261, January 2019. As of November 5, 2019: https://fas.org/sgp/crs/misc/R45261.pdf

Tak, Sangwoo, Kathleen Grattan, Les Boden, Al Ozonoff, and Letitia Davis, "Impact of Differential Injury Reporting on the Estimation of the Total Number of Work-Related Amputations," *American Journal of Industrial Medicine*, Vol. 57, 2014, pp. 1144–1148.

United States Census Bureau, "Statistics of U.S. Businesses (SUSB)," webpage, undated. As of July 4, 2019: https://www.census.gov/programs-surveys/susb.html

Viscusi, W. Kip, and Joseph E. Aldy, "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World," *Journal of Risk and Uncertainty*, Vol. 27, No. 1, 2003, pp. 5–76.

Viscusi, W. Kip, Wesley A. Magat, and Joel Huber, "Pricing Environmental Health Risks: Survey Assessments of Risk-Risk and Risk-Dollar Trade-Offs for Chronic Bronchitis," *Journal of Environmental Economics and Management*, Vol. 21, No. 1, 1991, pp. 32–51.

Washington Metropolitan Area Transit Authority, *Annual Safety Report*, 2015. As of November 5, 2019: https://www.wmata.com/about/board/meetings/board-pdfs/upload/022516_3A2015AnnualSafetyReportREV0224.pdf

Weil, David, "If OSHA Is So Bad, Why Is Compliance So Good?," *RAND Journal of Economics*, Vol. 27, No. 3, August 1996, pp. 618–640.

Winkelmann, Rainer, *Econometric Analysis of Count Data*, 5th ed., New York: Springer, 2008.

Wooldridge, Jeffrey, *Econometrics Analysis of Cross Section and Panel Data*, 2nd ed., Cambridge, Mass.: MIT Press, 2010.

World Bank, "Urban Population Growth (Annual %)—United States," webpage, 2018. As of July 24, 2019: https://data.worldbank.org/indicator/SP.URB.GROW?locations=US&name_desc=true

Zunjic, Aleksandar, Vladimir Sremcevic, Vera Zeravcic Sijacki, and Ana Sijacki, "Research of Injuries of Passengers in City Buses as a Consequence of Non-Collision Effects," *Work*, Vol. 41 (Suppl. 1), 2012, pp. S4943–4950.