

Engineering with Uncertainty: Monitoring Air Bag Performance

Jameson M. Wetmore

*Consortium for Science, Policy & Outcomes; School of Human Evolution & Social Change;
Arizona State University*

Keywords: engineering, uncertainty, monitoring, risk, social experiment

ABSTRACT: *Modern engineering is complicated by an enormous number of uncertainties. Engineers know a great deal about the material world and how it works. But due to the inherent limits of testing and the complexities of the world outside the lab, engineers will never be able to fully predict how their creations will behave. One way the uncertainties of engineering can be dealt with is by actively monitoring technologies once they have left the development and production stage. This article uses an episode in the history of automobile air bags as an example of engineers who had the foresight and initiative to carefully track the technology on the road to discover problems as early as possible. Not only can monitoring help engineers identify problems that surface in the field, it can also assist them in their efforts to mobilize resources to resolve problem.*

INTRODUCTION

Modern technological achievements – bridges that stand for centuries, buildings that seem to scrape the sky, communication systems that connect people around the world, and sophisticated medical techniques – can give the impression that engineers have an exhaustive knowledge of the material world. While these successes are certainly the result of careful engineering and extensive research, scholars and engineers alike have recognized that new technologies cannot be necessarily understood in every detail. Regardless of how much time one spends in the lab developing tests or running simulations there will always be situations that cannot be replicated and thus facets of the technology that are not fully understood. As civil engineer Henry Petroski put it, “absolute certainty about the fail-proofness of design can never be attained, for we can never be certain that we have been exhaustive in asking questions about its future.”¹ (p. 44)

The uncertainty inherent in new technologies is a constant challenge for engineers. In fact, one could argue that the job of engineers is to make balanced decisions in the face of

uncertainty. Engineers are by and large quite skilled at this task. Most of the time they understand technological systems well enough to ensure that they perform reasonably smoothly. Even though they must work with necessarily incomplete knowledge, they are nevertheless usually quite successful at satisfying regulatory, economic, safety, and design imperatives. The fact that major engineering disasters are rare is a testament to this diligence.

However, the scope of engineering knowledge during the initial design process may not include understandings that later prove vitally important. Sociologist Charles Perrow has argued that the complexities inherent in some modern technologies make it impossible for engineers to fully understand how those technologies will behave or the types of dangers they may generate in some unknowable future circumstance. As he forcefully put it, the “characteristics of high-risk technologies... suggest that no matter how effective conventional safety devices are, there is a form of accident that is inevitable.”¹ (p. 3) Petroski has similarly argued that “engineering is a human endeavor and thus it is subject to error.”¹ (p. 2)

The reality that certain kinds of problems cannot be accurately predicted or completely prevented presents an enormous challenge for engineers. It is a difficulty they struggle with on a daily basis. However, through experience and practice, engineers have developed strategies for dealing with the uncertainty inherent in their work. Scholars who study engineering have chronicled these strategies and developed a number of lessons that can help engineers successfully address this form of complexity.

Henry Petroski, for instance, has argued that engineers must diligently learn from the past to prevent future problems. He encourages engineers to engage in “forensic engineering” – the practice of investigating the causes of unforeseen failures.¹ He argues that failure is an important and perhaps necessary step in the development of robust designs and gives numerous

examples of how the careful analysis of disasters led to new understandings like the aerodynamic aspects of bridges and the important role that fatigue plays in the durability of materials. When engineers study these unforeseen consequences they broaden the scope of engineering knowledge and can prevent similar problems from occurring again.

Similarly, Charles Perrow, in his book, *Normal Accidents*, contends that engineers must recognize the limits of their knowledge and potential sources of problems so they can carefully analyze and prioritize the possible risks they introduce into society.² He divides these risks into three categories: risks that can be reduced through minor improvements, risks that will require substantial effort to address, and risks that far outweigh any benefit, at which point the technology should be abandoned. Perrow urges that risk assessment be made an important part of decision-making about new technologies.

While both learning from the past and carefully prioritizing current efforts are important ways to deal with uncertainty, neither will eliminate insufficient knowledge as a threat to engineering success. On a daily basis engineers must still make decisions in the face of uncertainty and deal with the results. Engineers need tools, frameworks, and approaches to constructively cope with the fact that there are limits to their knowledge.

A pair of scholars – philosopher Mike Martin and engineer Roland Schinzinger – have developed an approach to answer these needs. They contend that engineers will be much better prepared to deal with uncertainty if they approach their work as though it were a “social experiment.”^{3,4} They maintain – as do Petroski and Perrow – that any engineering “project is carried out in partial ignorance.”^{3 (pp. 89)} They argue that engineers will never have complete knowledge because of factors as diverse as not knowing how a piece of aluminum produced in a

factory will perform in the field, to the fact that multiple engineers in different working groups may not always be able to communicate clearly to each other.

Second, they argue that “the final outcomes of engineering projects... are generally uncertain.”^{[Error! Bookmark not defined.](#) (p. 90)} Despite the best efforts of engineers, bridges occasionally fall down, technologies do not always work as they were designed, and people do not always use machines in the way they were intended to be used. Engineers must test their products as extensively as possible, but must also recognize that time and money are sometimes legitimate constraints and it is never possible to test every scenario.

The result of these uncertainties, Martin and Schinzinger argue, is that the final testing of a technology is necessarily performed by (and on) those who use it after it leaves the production line. The design of any technology is not really finished or understood until it is being used (and misused) by the general public and the ramifications of the technology become clear. Thus, they contend that engineering should be seen as “an experiment on a social scale involving human subjects.”^{[Error! Bookmark not defined.](#) (p. 89)}

One of the important ramifications stressed by Martin and Schinzinger of viewing engineering as a social experiment is that just like natural scientists working in a lab, engineers must monitor the social experiments that they create. It can be tempting for engineers to turn their complete attention to a new project once they have finished building a device but, Martin and Schinzinger argue, because of the dangers to which engineering exposes the public, engineers have a responsibility to continue to assess the technology after it leaves their hands. Engineers should monitor the technology they produce as it is integrated into society to ensure that the transition is as smooth and as safe as possible.

Additionally, Martin and Schinzinger argue that viewing engineering as social experimentation should also compel engineers to obtain the informed consent of the public.³ If members of the public are going to be subjected to some uncertainties that may pose a danger to them, they should have some say in it. Because of the nature of engineering and the number of people affected by technologies, obtaining informed consent can be difficult. For this reason, Martin and Schinzinger urge engineers to widely disseminate (in an understandable form) information about the technology and the potential it could have to be harmful. When it is not practical to obtain consent from individuals, engineers should at least try to obtain it from representative groups.

Martin and Schinzinger argue that one of the most important steps engineers can take is to acknowledge that, because they cannot understand situations as completely as they would like, the work they do as engineers is “inherently risky.”[Error! Bookmark not defined.](#) (p. 89) Once engineers recognize the unpredictability and danger of their profession, they can better prepare themselves, their colleagues, and even the public for the future. Engineers who think of their work as a social experiment can better recognize the gravity of their actions, more clearly see the need to be reflective in their decision making, and be more willing to prepare for problems that may result from incomplete understanding.

This paper examines the recent history of the automobile air bag to demonstrate how engineers can successfully use the idea of engineering as social experimentation to anticipate, address, and contain uncertainty. In this instance, a number of engineers recognized the uncertainty inherent in the technology they were designing and took steps to monitor, assess, and limit the dangers they were introducing.

In addition to providing an example of engineers monitoring a new technology for unforeseen circumstances, the case can also help engineers deal with the important question “What should be done when the monitoring reveals a problem?” In the case of the air bag, a number of problems were discovered during the mid-1990s. Unfortunately, the complexity of the technology and the ways in which people interacted with it led to a number of fatalities. Because the engineers involved recognized from the beginning that there might be unpredictable results, they were prepared for potential problems, able to quickly pool their resources and inform the public, and successfully resolved the situation.

The idea of approaching engineering as a social experiment is immensely useful because it offers a way to envision – and points towards steps to deal with – the problem of uncertainty that is inherent in engineering practice. This is an example of engineers who acknowledged that they did not fully understand how the technology they had designed would work once released to the public, and chronicles the steps they took to prepare for potential problems and to gather new information. This example demonstrates that framing engineering as social experimentation is a useful way to approach technical projects, prepare for difficult situations, formulate responses to problems, and ultimately save lives.

A BAG FULL OF UNCERTAINTIES

In the late 1980s and early 1990s, a group of engineers became reasonably concerned with the first widespread launch of a complicated technology. As a result of government regulation, marketing programs, and popular demand, millions of air bags were being installed in American automobiles.^a The idea for the technology was first developed in the 1950s and throughout the

^a The history of air bags has been marked with numerous complications and disagreements.^{5,6} By the late 1980s there was broad consensus that the technology should be installed in most (if not all) vehicles, but engineers have

'60s and '70s countless engineers at automobile manufacturers and suppliers around the world had been refining the concept and testing it in laboratories and on the road. Despite this extensive experience, in the late 1980s, engineers were concerned about the safety of the technology they were building and promoting.

This concern was shared not only by the engineers at the automobile manufacturers, but also those employed by insurance companies, safety organizations like the National Safety Council, and the government agency that established air bag regulations – the National Highway Traffic Safety Administration (NHTSA). Their experience with air bags, as well as with technology in general, had convinced them that there were a number of disturbing uncertainties about the technology. Although the basic idea of an air bag – to inflate a bag in front of an occupant during a collision in order to distribute the load of the crash widely over the occupant's body – was simple enough, getting it to work routinely and successfully was an immense engineering challenge.

There were two main sources of uncertainty. The first of these was technical uncertainty. Air bags are not simply a “plug in” component. They are a complicated system that must be designed to be compatible with other systems – many of which cannot be controlled. For instance, it is incredibly difficult to design a sensor that reliably triggers an air bag when it is needed. Every crash is different. There are different angles, speeds, rates of deceleration, and size and mass of objects being hit. Some of these may produce very similar effects in the first millisecond (when the electronics must decide whether or not to inflate the bag), but very different effects when the crash forces transfer to the occupant. It is also important to correctly configure the inflation rate of the bag for the particular type of crash. If the bag comes out too

had to struggle with competing ideas of how air bags should be designed and the role they should play in automobile safety.

slowly, it may inflate too late to offer any protection. If it comes out too fast, it could be very dangerous and perhaps even deadly. Each of these facets differs from car to car and from situation to situation. Working primarily in laboratories with a finite number of testing opportunities, engineers had no way of knowing how their technologies would respond to the infinite number of possible crash scenarios on the highway. Hence engineers did not know exactly how the air bags would deploy (or whether they would indeed deploy) in a crash.

The second source of uncertainty was social uncertainty. Engineers did not know exactly how people would interact with their air bags. Would the occupants be buckled or unbuckled when a collision began? Would they be sitting two inches away from the bag or two feet from the bag? Would there be one person in the passenger seat or four? Would the passenger be wearing the combination lap/shoulder belt, or simply the lap belt? Again, to optimize the safety of the occupants in each of these scenarios would require very different air bags. Engineers tried to design for as many scenarios as possible, but knew that the driving public would use their cars in ways the engineers did not expect.

The combination of these two categories of uncertainty, including the fact that they could easily compound one another, made predicting the effect of putting air bags in automobiles very difficult. Engineers could never test or account for every possible permutation, especially when small changes in the size of the vehicles involved, the position of the occupant, or the crash impulse could lead to very different results. Engineers close to air bag design and production understood that their knowledge about the technology had significant limitations.

LIMITING THE UNCERTAINTY

Whether due to their goal of being professionals, a concern about product liability, or a combination of several factors, many of the engineers involved in air bag production and

promotion chose to keep working on air bags even after the technology left their hands. They had spent countless hours designing, testing, and re-engineering air bags and had an informed idea of what would happen when air bags were released to the general public. They also recognized that there was a potential for problems that they could not have accurately predicted. Implicitly, the engineers that dealt with air bags behaved as though they were engaged in a “social experiment.” They took a number of proactive steps in an effort to better understand the technology and look out for the safety of those using their product.

First they continued to support the effort that had already been underway for several years to convince the American public to put on their seat belts.⁷ Although much of this was done by marketing professionals and public officials, engineers played a crucial role in the process. They helped prepare public education materials, gathered statistics that demonstrated the benefits of wearing belts, and even testified before state legislatures in an effort to promote laws which mandated the use of seat belts.^{8,9} Most engineers believed that not only would such belt use make occupants safer in itself, but it would also make designing and predicting the effects of an air bag easier because people would be much more likely to be in a safer position should the bag deploy.^b

Second, engineers at the automobile manufacturers, as well as at NHTSA, the Insurance Institute for Highway Safety, and a handful of universities, continued to collect laboratory data on air bags.^{11,12} They tried to replicate as many crash scenarios as they could by running tests to better understand the effects of hitting trees, hitting cars at different angles, and hitting vehicles from the side rather than simply head-on. And they developed new dummies and tests so that

^b The question of whether to design air bags for people wearing seat belts or for people otherwise unrestrained has been a source of significant controversy through the history of the technology.^{5,6} NHTSA regulations, however, have required since the 1980s that air bags be tested with unbelted 50th percentile male dummies in an effort to ensure they provide some benefit to unbuckled occupants.¹⁰

they could better replicate the effects of air bags on children, women of different weights and stature, and infants in child safety seats.^{13,14} While none of these tests would tell them precisely what would happen in a highway collision, each new piece of information helped them to better understand potential problems.

Finally, the auto safety community also took one of the steps that Martin and Schinzingler have deemed extremely important: they carefully monitored the performance of air bags on the road. Insurance companies examined the claims of their policyholders closely and analyzed them for trends.¹⁵ Automakers followed up media reports about crashes involving their products, analyzed the specific scenarios, and conducted new crash tests to help them better understand what they were finding. A number of offices and groups within NHTSA were charged with monitoring air bags on the road. NHTSA's Office of Defects Investigations gathered information on possible air bag side effects from the public complaints it received; its National Center for Statistics and Analysis carefully tracked and analyzed every U.S. traffic fatality in which an air bag was present; and its Special Crash Investigation Program kept an eye out for any air bag problems when it visited crash scenes.^{16,17} In addition, NHTSA formed a special "Air Bag Technology Review Group" devoted solely to collecting information from a variety of sources inside and outside of NHTSA in order to discern air bag difficulties before they could become serious problems.

MONITORING AIR BAG PERFORMANCE

During the late 1980s and early 1990s, these monitoring efforts helped insurance companies, automobile manufacturers, and NHTSA to uncover a handful of problems with air bags. By 1992, the evidence they had gathered led NHTSA researchers to estimate that 25,000 people had

been injured by the devices between 1988 and 1991.¹⁸ For the most part, the injuries reported were not severe. NHTSA rated ninety-six percent of them “minor,” nearly four percent “moderate,” and two-tenths of a percent “serious.” The studies also revealed a few trends. For instance NHTSA determined that a number of drivers received forearm burns and arm and face abrasions during collisions that had triggered an air bag deployment – injuries that were typically deemed “minor to moderate.”¹⁹

As these problems were pinpointed, engineers made every effort to quickly address them. For example, once they knew to specifically look for potential sources of air bag burns, engineers traced at least part of the problem to the hot nitrogen gas generated to inflate the air bag.²⁰ Modern air bags have vents designed to release excess gas and ensure that they have a reasonable amount of “give” when occupants make contact with them. Vehicles with the vents placed at the “three o’clock” and “nine o’clock” positions on the bag forced out the hot gas close to where many drivers held the steering wheel. Thus the heat of the gas would give drivers minor burns on their forearms.^c

Other burns, they found, were the result of the fact that when air bags deploy, they do not just move directly forward toward the occupant. The bags are folded inside the steering wheel or dashboard and move both toward and perpendicular in every direction to the occupant as they inflate. Engineers at the automakers deduced that some abrasions were caused by the way this perpendicular movement, as well as the bulging that can occur when the bag first fully inflates, could drag the fabric of the bag across the surface of the skin.

Once they determined the causes of these burns and abrasions, automotive engineers were able to redesign air bags and resolve the problem. By 1991, most companies had moved

^c A number of news sources reported that these burns were the result of the chemicals used to inflate the bags, but most engineers ultimately concluded that they were caused by the high temperatures of the gases, not the chemical makeup of the materials.

the exhaust vents away from the occupant's arms to the 12 o'clock position and used a tether inside the bag to keep the bag from bulging toward the occupant thereby reducing the risk of abrasions.²¹ These were not perfect fixes, as current air bags can still cause burns and abrasions, but they did significantly alleviate the problems.

INFORMING THE PUBLIC

For the most part this monitoring process initially found only minor problems that could be fixed with a bit of re-engineering. The continuing analysis of air bag performance did, however, reveal some potential problems that were more disconcerting to the auto safety community than minor burns and abrasions. In the fall of 1991, engineers at NHTSA's Vehicle Research and Test Center in East Liberty, Ohio, ran several barrier tests with a rear-facing infant safety seat in front of a passenger-side air bag. In one test an air bag impacted with an infant safety seat and launched the infant seat into the backseat.²² NHTSA engineers argued that because most rear-facing child safety seats extended into the area displaced by a fully deployed air bag, dangerous jolts like this one could be a common occurrence. This was a situation that likely should have been foreseen and dealt with, but had not been adequately addressed. In addition to these disturbing tests, auto manufacturers and NHTSA had become aware of at least five fatalities that they believed would not have occurred had air bags not been present. [Error! Bookmark not defined.](#)

The organizations involved in auto safety responded to these concerns in two ways in the early 1990s. First, the amount of testing at laboratories was further increased. NHTSA, for instance, sought to better understand the problem through its own lab testing and through a joint research project with the Society of Automotive Engineers (SAE).^{23,24} Second, NHTSA, automakers, and the insurance companies began an extensive program to convince parents to

Deleted:

place rear-facing child safety seats in the back seat of their automobiles. They publicized the importance of putting these child safety seats in the back through their normal channels—press releases, doctors, public information pamphlets, and the media.^{25,26,27}

However, the auto industry claimed that this was not enough. They believed it was necessary to post a warning of the dangers of air bags in every automobile. In essence they believed that the driving public should have some sort of informed consent in regards to the possible dangers. None of the companies, however, wanted to do this voluntarily because they feared that a competitor could gain a sales advantage by not warning their buyers. Thus in February of 1992, the Motor Vehicle Manufacturers Association (MVMA) petitioned NHTSA to require a “consumer information label” that would remind occupants of the dangers of air bags, the need to wear their seat belts, and the need to put rear-facing child safety seats in the back seat.²⁸

This request led to a series of debates over how to best convey the appropriate information to the public. The groups involved had to deal with a problem that commonly occurs with new technologies: how does one give the public adequate warning about the potential dangers without frightening them to the point that they reject the technology? NHTSA officials proposed the following label in an effort to inform without instilling fears:

For maximum safety protection in all types of crashes, you must always
wear your safety belt.

Do not install rearward-facing child restraints in any front passenger
seat position.

Do not sit or lean unnecessarily close to the air bag.

Do not place any object over the air bag or between the air bag and
yourself.

See the owner’s manual for further information and explanations.^{29 (p. 59046)}

Because of safety concerns as well as the fear that air bag injuries might lead to numerous lawsuits, the Big Three U.S. automakers (Ford, Chrysler, and General Motors) were

concerned that this label was not powerful enough. They wanted the labels to emphasize not just how to be safe, but also why these instructions were so important. The automakers wanted the public to understand some of the significant limitations of air bags so that a false sense of security would not cause drivers and passengers to neglect their seat belts. The American manufacturers countered with the following option:

! CAUTION :

Air bags are not designed to reduce the risk of injury in rollovers or in rear, side, or low-speed-frontal crashes.

Air bags inflate with great force, faster than you can blink your eyes. An occupant who is too close to the inflating air bag can be seriously injured.

An inflating passenger air bag can seriously injure a child in a rear-facing child restraint. Follow all instructions in the vehicle owner's manual regarding child restraints.

Do not place packages or other objects between the air bag and the occupant. Such objects could injure you if the air bag inflates in a crash.³⁰

NHTSA officials settled for a compromise of sorts. They required the text of the label as they had originally proposed, but added the heading, "CAUTION, TO AVOID SERIOUS INJURY:" in an attempt to satisfy the demands of the automakers.

DEALING WITH INCREASING CONCERN

The addition of the label in new cars calmed the concerns of most auto safety experts (and automotive industry lawyers) for a few years, but engineers did not stop collecting and monitoring ever increasing amounts of data about air bags on the road. By 1995, these efforts had yielded further disturbing findings.³¹ In March of that year, the Insurance Institute for Highway Safety blamed air bags for the death of eleven people and automakers were becoming increasingly concerned.³² What was particularly alarming was that many of these fatalities occurred in very low speed collisions, which should have produced little more than bruises.

NHTSA engineers researched the handful of documented fatalities and developed a

theory for how the deaths were occurring. They argued that because drivers typically brake in anticipation of a frontal crash:

the occupant moves forward toward the windshield and instrument panel prior to air bag deployment. The air bag inflator must produce enough energy to inflate the air bag fully in about 25 milliseconds to “cushion” the occupant before the occupant strikes the vehicle interior. The energy necessary to inflate the air bag in such a short time interval can cause injury or even fatality to an occupant...³³ (p. 46555)

NHTSA officials also noted that some specific groups were more likely to experience negative effects from air bags than others. In particular they singled out small-statured and/or older people not wearing seat belts, infants in rear-facing child restraints, unrestrained children in the front seat, out-of-position occupants, and persons with disabilities.

Things got worse before they got better. In November of 1996, NHTSA’s statistics cited air bags as the cause of death for twenty adults as well as thirty children.³⁴ As they monitored the technology and recalculated the risks involved, NHTSA engineers raised their warnings and called for parents to put all children age twelve and under in the back seat, rather than just those infants in rear-facing safety seats.³⁵ They also issued a warning to shorter women drivers who they believed were especially at risk because they often sat close to the steering wheel and could be injured or killed during the “burst out” phase of air bag inflation. By the spring of 1997, auto safety researchers had found that air bags took the lives of 3.5 children for every one that they saved.³⁶ The media jumped on the story and there was widespread outrage in newspapers, magazines, editorial columns, and television news programs. Many called for air bags to be ripped out of automobiles.^{37,38}

This proposal frightened most engineers. They were certainly concerned about the fatalities, but they believed that air bags were saving many lives and that to abandon the technology would be a mistake. Unfortunately there was no simple technical fix for the problem.

Redesigning the technology would take a great deal of time and would not be able to address the millions of air bags already on the road. A recall would be expensive, difficult, and might not even solve the problem since air bag design entailed not only the bag, but the shape of the passenger compartment, steering wheel, dashboard, windows, etc. The engineers involved, therefore, looked beyond the artifacts they were building for at least an interim remedy.

FIRST AID FOR AIR BAGS: EDUCATING THE USER

In developing a solution to the problem of air bag fatalities, the engineers involved recognized that the automobile is not simply a collection of steel, rubber, fluids, and electronics – it is a human-machine system. It is not only the design of the vehicle that determines the effects of a crash, but the way the occupants behave as well. Since the engineers could not quickly fix the hardware, they argued that the best way to eliminate or significantly lessen air bag injuries would be for individual motorists to change their practices in the car. After analyzing the fatalities and conducting experimental crash tests, the engineering researchers developed a revised set of responsibilities for automobile occupants that would compensate for the problems with air bags and, in the long run, enhance the safety of occupants regardless of whether there was an air bag present. The new motorist responsibilities were:

1. Properly restrain all passengers;
2. Put all children up to age twelve in the back seat; and
3. Maintain at least ten inches between yourself and the air bag.³⁵

Once these three basic safety measures were developed, the automobile companies, safety organizations like the National Safety Council, NHTSA, and the insurance companies began a concerted effort to re-educate the public. On May 21, 1996, the National Safety Council announced the formation of the Air Bag Safety Campaign, a joint project between NHTSA and

nearly every major automobile company, air bag supplier, and automobile insurance company that operated in the United States.³⁹

This campaign was different from previous efforts to educate the public about air bags in three significant ways. First, the nation's driving public was given many more responsibilities than in previous warnings. Sitting back from the air bag and putting children in the back seat required a significant change in habit for many people and had never been strongly recommended before. Second, the education effort in the late 1990s was much larger and better funded than any of the previous attempts to tell people how to best use air bags. And finally, unlike many previous warnings, the educational materials forcefully stressed the potential consequences of not following these steps. Pamphlets no longer offered suggestions on how to act. Instead they were titled with phrases like: "The Air Bag that Saves Your Life Could KILL Your Child."⁴⁰ One particular television commercial, for instance, first showed an air bag slamming into a rear-facing child safety seat at full speed to demonstrate the violence of the crash and then again in slow motion to show how the infant dummy is jolted and thrown about.⁴¹

NHTSA also decided to revise the labels that all manufacturers were required to install on their sun visors. After hearing comments from all the interested parties – including engineers at the automobile manufacturers, insurance companies, and safety organizations – NHTSA scrapped the "consumer information label" and developed a new "warning label." The newly required label included a picture of an air bag shattering a child safety seat and was worded much more strongly:

WARNING

DEATH or SERIOUS INJURY can occur

Children 12 and under can be killed by the air bag

The BACK SEAT is the SAFEST place for children

NEVER put a rear-facing child seat in the front unless air bag is off

Sit as far back as possible from the air bag

ALWAYS use SEAT BELTS and CHILD RESTRAINTS⁴² (p. 60217)

The groups involved worked to make sure that warnings about the dangers of air bags and instructions on how to avoid these dangers could be found everywhere – from automobile insurance bills to television and radio commercials; from activity packets distributed in elementary schools to labels posted in cars themselves.^{43,44,45}

INFORMED CONSENT

This public information campaign about the dangers of air bags did not, however, satisfy everyone. Many reporters, columnists, and members of the public argued that the air bag experiment had proven to be a dangerous failure and they wanted their air bags removed. Existing NHTSA regulations, however, made this extremely difficult. Automobile dealers and repair shops were prohibited by law from disabling any federally mandated safety device – including air bags. Legally, private citizens were allowed to personally disable their own air bags but to do so required a certain amount of expertise. If they made a mistake, they could trigger a dangerous accidental air bag deployment.

The frustration caused by these limitations led to significant public outrage. Newspapers printed editorials denouncing NHTSA as a “Big Brother” government agency that was willing to sacrifice women and children to save strong men.³⁸ NHTSA offices received thousands of phone calls and letters from people begging to get their air bags removed.⁴⁶ In essence, a vocal number of the general public argued that they wanted the right of informed consent in the air bag experiment that NHTSA had helped to create. They wanted no part of the uncertainty or danger of air bags.

The first reaction of those in the air bag community was to resist this public uproar. They

had a great fear that if NHTSA allowed anyone to disable their air bag, hundreds of thousands – if not millions – would do so. This frightened them for two important reasons. First, they believed that air bags had been a great benefit to the public by saving an estimated 1500 lives and that it would be irresponsible to make the technology a scapegoat.^d Second, they feared that rampant disconnections would amount to a public condemnation of a technology they had promoted as a valuable safety device for nearly a decade. This could open the door to a barrage of new lawsuits and force an expensive redesign of future automobile models. The automobile manufacturers, insurance industry, and organizations like the National Safety Council maintained that rather than let car owners do as they pleased, the focus of the auto safety community should be on ensuring that motorists carried out the duties already allocated to them in order to eliminate the adverse effects and maximize safety.

The resulting debate played out in newspapers, government hearings, and private correspondence between the organizations involved. Ultimately, however, the decision was made to give the general public at least some degree of informed consent – but the manufacturers, insurance companies, and safety organizations wanted to make sure that the emphasis was on “informed.” In November of 1997, NHTSA instituted a new regulation that would give some automobile owners more control of the technology by allowing on/off switches to be installed on their air bags.⁴⁹ To make sure that people who were at no danger from their air bags did not turn off the devices, car owners had to first apply and get approval from NHTSA for an on/off switch. The regulation required concerned individuals to first read a NHTSA information packet and then demonstrate that they were especially at risk of being injured by an air bag. NHTSA’s definition of “especially at risk” was limited to drivers who had at least one of

^d Air bags were credited with saving 1500 lives in early 1997.^{47 (p. 832)} As of July 2005, air bags were credited with saving over 18,000 lives in the United States.⁴⁸

three issues: 1. Could not maintain ten inches between themselves and the steering wheel; 2. Had to transport more children than would fit in the back seat; or 3. Had a medical condition that made air bags a significant threat to their health.

RESOLVING THE PROBLEM

As the debates over on/off switches developed and the campaign to educate the public was waged in the mid-to-late 1990s, automotive engineers were also looking for ways to redesign air bags to limit the risk to automobile occupants. They found that one of the reasons the bags had been so dangerous is that they were designed primarily with one test in mind – NHTSA’s New Car Assessment Program (NCAP) – the test that awarded vehicles with the coveted government safety rating stars. Engineers found that the tests, which were run at high speeds using adult male dummies, favored very fast and powerful air bags.^{50 (p. 30689)} Such powerful air bags, however, were not as safe for out-of-position occupants and occupants of smaller stature (including most women and children).

Automotive engineers wanted to redesign these bags as quickly as possible. Specifically they wanted to depower their bags to make the initial “punch-out” less violent. To make this redevelopment process faster, NHTSA officials reworked the testing requirements. Rather than requiring that complete vehicles be driven into a solid barrier at 30 mph with an unbelted dummy, NHTSA required a 30 mph sled test, which simulated the deceleration of a crash in the vehicle’s interior without using (or destroying) the entire vehicle.⁵¹ The benefit of this approach for automakers was that it could be repeated more cheaply and predictably than a regular crash test. Automakers therefore did not have to “over-design” their air bags to ensure that they could pass the more unpredictable full crash tests and this allowed them to depower with the confidence that they could still meet NHTSA regulations. The result was that the new design

might not provide quite as much protection in some violent crashes, but would be significantly “more forgiving” to smaller occupants.^{52,e}

Despite these important design changes, the efforts to educate the public made the most significant contributions to increasing safety at least in the short term. The brochures, TV coverage, newspaper articles, and public presentations helped stimulate a considerable change in the practices of American automobile occupants. NHTSA’s statistics on observed seat belt use rose from 61 percent at the beginning of 1996 to 69 percent by the end of 1998.^{54 (p. 4)} Restraint use for infants (1–12 months) rose from 85 percent to 93 percent, for toddlers (1-4 years) from 60 percent to 87 percent, and for children (5-15 years) from 65 percent to 69 percent.^{55 (pp. 4-5)} And parents were also putting their children in the back seat much more often than they had been previously.⁵⁶

By the year 2000, to the relief of all in the auto safety community, the number of deaths being attributed to air bags each year had dropped significantly. The number of fatalities per year dropped from a high of forty-three in 1997 to eleven in 2000, even though the number of air bags being sold increased dramatically. The rate of air bag fatalities per million air bags dropped from 1.35 in 1994 to 0.15 in 2000.^{43 (p. 5)} Most experts believe that because the immediate changes to air bag design had affected only a small number of the total air bags in the nation’s fleet, the only explanation for the decrease in fatalities is that the education effort and the public’s acceptance of new responsibilities was widespread and effective in mitigating the problem.

CONCLUSION

^e More recent research has shown that these depowered bags not only made them safer for small women and children, but actually lowered the risk of driver death across the board.⁵³

It is difficult to say how long it would have taken to discover some of the negative effects of air bags if engineers had not been on the lookout for them. With over 40,000 highway fatalities in the United States every year, it can be almost impossible to discern patterns like air bag injuries from aggregate data. Because engineers dealing with air bags approached their work as though it was a social experiment they were prepared to both find and remedy the problems that developed. They knew that their understanding was limited and that there was a potential for serious problems, so they took a number of steps to monitor the technology and deal with its shortcomings as they emerged. Thanks to these efforts, the number of people killed each year by air bags has been reduced to the point where it is difficult to measure, and the number of people saved by air bags in the United States since 1997 is over 15,000.⁵⁷

Applying the idea of engineering as a social experiment was not an easy or straightforward process. Engineers at work are usually portrayed as building or designing. But there are aspects of the job that often go unnoticed and that are quite important to society. For the last decade, engineers involved with air bags did not simply sit in a lab and research and design. Rather, to fulfill their responsibility to “hold paramount the health, safety, and welfare of the public,”^f they have had to travel to other cities and states to inspect car crashes, compile injury statistics from police departments across the country, exchange information with engineers from other industries and the government, inform the public about potential dangers, stand before congressional hearings, be interviewed by the media, find social solutions to technical problems, and some of them even had to face the rage of parents whose children had been killed by air bags. They did not always have a completely accurate picture of the risks, but they

^f The code of ethics of nearly every professional engineering society includes this as one of the foremost responsibility of engineers.⁵⁷

recognized their own uncertainties and took numerous steps to seek out small problems before they became big problems.

The engineers involved did not, however, accomplish this task by themselves. They were successful because they sought out and received a great deal of support from the organizations for which they worked. The other administrators and employees at the insurance companies, automobile manufacturers, safety organizations, and NHTSA recognized the importance of the engineers' concerns. They were willing to give engineers the time, money, resources, and assistance they needed to monitor air bags in the field. The engineers were able to convince others that developing technology involves a great deal of uncertainty and that steps must be taken to resolve this uncertainty both before and after a technology is built and sold.

In part because of this early involvement, engineers also received a significant amount of support when they came to the realization that the "social experiment" was going badly. The task of educating the public while simultaneously redesigning air bag technology required an enormous amount of resources. Regulators, senators, advertising executives, lawyers, public officials, insurance company employees, members of the media, and many others worked together with engineers to develop and implement a solution. In the end the solution they devised was not one that may seem readily obvious to some engineers since a major part of it relied on advertising strategies to create social change. Yet the gravity of the problem caused everyone involved to consider a wide variety of options and think outside their normal disciplines. The final decision was based not only on the research done by engineers in the laboratory and in the field about what caused injuries, but also on the insistence by many in the engineering community that a social solution must be pursued because a safe and effective technical solution could not be implemented soon enough. Without the early collaboration

among institutions and individuals from a wide variety of backgrounds, it would have taken much longer to both understand and deal with the problem.

This case study of air bag engineers is quite complex. It is not simply a story about professionalism, policymaking, or public education. It involves all of those things and more. It is an example of the messy way in which society and technology are intertwined in the modern world, and the complicated circumstances in which engineers must act. Martin and Schinzinger's idea that engineering is a social experiment is a useful tool for engineers trying to figure out how to act responsibly within this complex world. It encourages them to simultaneously recognize the limits of their knowledge, attempt to foresee potential problems, and take steps to resolve unforeseen problems that occur months – even years – after the product leaves the assembly line. Because the engineers involved in developing air bags recognized the uncertainty inherent in the technology and the potential risks involved, they actively studied the effects of the technology in the field. Their research, and the steps they took to address the problems they found, not only prevented numerous minor injuries, but likely also saved many lives. They succeeded in these efforts in large part because they not only understood the dangers, but were able to enroll a number of other groups and individuals in their efforts. The world that engineers are building will involve risks that are not yet understood. If engineers are both reflective and proactive and take steps to monitor these changes, the transition to this future world will be much smoother and safer.

Address for correspondence: Jameson M. Wetmore, Consortium for Science, Policy & Outcomes, Arizona State University, PO Box 874401, Tempe, AZ 85287-4401, USA; email: jameson.wetmore@asu.edu.

Acknowledgements: The author would like to thank Deborah Johnson and two anonymous reviewers for their very useful suggestions for this paper. The research for this article was supported by the Department of Science, Technology & Society at the University of Virginia, National Science Foundation Research Grant SES-0080600, and the Dwight David Eisenhower Transportation Fellowship Program.

| REFERENCES

1. Petroski, H. (1992) *To Engineer is Human: The Role of Failure in Successful Design*. Vintage Books, New York.
2. Perrow, C. (1984) *Normal Accidents: Living with High-Risk Technologies*. Basic Books, Inc., New York.
3. Martin, M.W. & Schinzinger, R. (2004) *Ethics in Engineering*. McGraw Hill, Boston.
4. Schinzinger, R. & Martin, M.W. (2000) *Introduction to Engineering Ethics*. McGraw Hill, Boston.
5. Graham, John D. (1989) *Auto Safety: Assessing America's Performance*. Auburn House, Dover, Mass.
6. Wetmore, J. M. (2004) Redefining Risks and Redistributing Responsibilities: Building Networks to Increase Automobile Safety. *Science, Technology & Human Values* **29**(3) Summer: 377-405.
7. Traffic Safety Now (1992), *An American Revolution: The Story of Traffic Safety Now*. Washington D.C.
8. Rouhana, S.W., Horsch, J.D. & Kroell, C.K. (1989, October) Assessment of Lap-Shoulder Belt Restraint Performance in laboratory Testing. *Proceedings of the 33rd Stapp Car Crash Conference*, Washington, DC (SAE paper No. 892439).
9. Evans, L. (1995) How We Know Safety Belts Reduce Injury and Fatality Risks, in: J.P. Smreker, D.F. Huelke, & D. Haenchen (eds.) *Issues in Automotive Safety Technology: Offset Frontal Crashes, Airbags, and Belt Restraint Effectiveness*. Society of Automotive Engineers: Warrendale, PA: 7-10.
10. NHTSA (1997, March 19) Temporary Amendment – Final Rule. *Federal Register* **62**: 12960-12975.
- a1. *Proceedings of the 35th Stapp Car Crash Conference*. San Diego, CA., November 18-20, 1991, Society of Automotive Engineers, Warrendale, PA.
- a2. *Proceedings of the Fourteenth International Conference on Enhanced Safety of Vehicles (ESV)* Munich, Germany, May 1994. US Government Printing Office, Washington, D.C.: 1995-381-067.
- a3. O'Connor, C.S. and Rao, M.K. (1992, November) Development of a Model of a Three-Year Old Child Dummy Used in Air Bag Applications. *36th Stapp Car Crash Conference Proceedings*, Society of Automotive Engineers, Warrendale, PA: 81-102 (SAE paper no. 922517).
- a4. Kallieris, D., Stein, K., Mattern, R., Morgan, R. & Eppinger, R. (1994) The Performance of Active and Passive Driver Restraint Systems in Simulated Frontal Collisions. *Proceedings of 38th Stapp Car Crash Conference* (SAE paper 942216).
15. Werner J.V. & Sorenson, W.W. (1994) Survey of Airbag Involved Accidents: Analysis of Collisions, Characteristics, and System Effectiveness and Injuries. *Society of Automotive Engineers International Congress and Exposition*, Detroit, Michigan (SAE paper 940802).
16. NHTSA (1997) *Cases From the Special Crash Investigation Program*. US Dept of Transportation, Washington D.C.
17. Malliaris, A., DeBlois, J., Digges, K. (1996, February) Air Bag Field Performance and Injury Patterns. *Occupant Protection Technologies for Frontal Impact, Current Needs and Expectations for the 21st Century*. Society of Automotive Engineers, Warrington, PA: 73-78 (SAE paper 960659).
18. Knotts, B. (1992, December 20) Agency Gets Real About the Air Bag. *South Florida Sun-Sentinel*: 1G, 2G.
19. Sullivan, L.S. & Kossar, J.M. (1992, February) *Air Bag Deployment Characteristics, Final Report*. NHTSA, Washington, D.C.
20. Huelke, D.F., Moore, J.L., Compton, T.W., Samuels, J. & Levine, R.S. (1995, April) Upper Extremity Injuries Related to Airbag Deployments. *Journal of Trauma-Injury Infection & Critical Care* **38** (4): 482-488.
21. Jacobus, J. (1991, October 21) Trip Report—Air Bag Technology Review Group October 2/3, 1991. NHTSA memorandum.
22. Sullivan, L.K. (1992, October) *Child Restraint/Passenger Air Bag Interaction Strategies—Final Report*. NHTSA, Washington, D.C.
23. Hollowell, W.T. & Hitchcock, R.J. (1993, September) The National Highway Traffic Safety Administration Program to Improve Frontal Crash Protection. *26th International Symposium on Automotive Technology and Automation*, Aachen, Germany.
24. Sucki, S.L., Ragland, C., Hennessey, B. & Hollowell, T. (1995) NHTSA's Improved Frontal Protection Research Program. *1995 SAE International Congress and Exposition*, Detroit, Michigan, February 27-March 2 (SAE paper no. 950497).
25. U.S. Department of Transportation (1991, December 10) NHTSA Warns Parents About Child Safety Seat Use in Cars with Air Bags. Press Release, Washington, D.C.
26. Rather, D. (1991, December 10) Air Bags May be Dangerous for Babies in Rear-Facing Car Seats. CBS Evening News, television broadcast.
27. Finkelstein, D. (1992, January 14) Warning: Child Seat Plus Air Bag Can Add Up to Danger. *St. Louis Post-Dispatch*: 7D.

28. Hanna, T.H. (1992, February 27) letter to Jerry R. Curry, Administrator, NHTSA, in: NHTSA Docket PRM-208, Number 88.
29. NHTSA. (1992, December 14) Federal Motor Vehicle Safety Standards; Occupant Crash Protection. *Federal Register* **57** (240): 59043-59053.
30. Carr, T.J. (1993, February 12) Letter to Mr. Barry Felrice, Associate Administrator for Rulemaking, NHTSA. In Docket 74-14 Notice 79, Number 23.
31. Hollands, C.M., Winston, F.K., Stafford, P.W. & Lau, H.T. (1996, June) Lethal Airbag Injury in an Infant. *Pediatric Emergency Care* **12** (3): pp. 201-202.
32. Insurance Institute for Highway Safety (1995, March 18) Air Bag Injuries are Mostly Minor but a Handful are Serious, Even Fatal. *IIHS Status Report* **30** (3): 2, 4.
33. NHTSA (1995, November 9) Request for Comments. *Federal Register* **60** (217): 56554–56559.
34. O'Donnell, J. & Healey, J.R. (1996, October 23) Feds Now Say Air Bags Pose Greater Danger. *USA Today*: 1B.
35. NHTSA (1996, November 22) NHTSA Announces Comprehensive Plan to Improve Air Bag Technology and Reduce Air Bag Dangers. Press Release, Washington D.C.
36. O'Donnell, J. (1997, March 17) Key Air Bag Promoter Backs Off. *USA Today*: 1A.
37. Reiner, S. (1996, November 12) The Airbag Guys Forgot Just One Small Thing. *Baltimore Sun*.
38. Beck, J. (1996, December 4) Sexist and Risky Air Bags. *Journal of Commerce*: 6A.
39. U.S. Department of Transportation (1996, May 21) Secretary Pena Announces Government/Industry Coalition for Air Bag Safety. Press Release, Washington, D.C.
40. NHTSA (1997), The Air Bag that Saves Your Life Could KILL Your Child. pamphlet, Washington, D.C.
41. Air Bag & Seat Belt Safety Campaign (1998), Infants & Air Bags. television commercial, Washington, D.C.
42. NHTSA (1996, November 27) Federal Motor Vehicle Safety Standards; Occupant Crash Protection. *Federal Register* **61** (230): 60206–60221.
43. Air Bag and Seat Belt Safety Campaign (2001) *Crisis to Progress: 5 Years of Air Bag Safety in America*. National Safety Council, Washington, D.C.
44. NHTSA (1996, September) Air Bag Alert. Brochure, Washington, D.C.
45. Anonymous (1996, May 21) How to Help Air Bags Protect You. *USA Today*: 2B.
46. Womack, John (2000, July 6) Deputy Chief Counsel, NHTSA, (interview).
47. NHTSA (1997, January 6) Air Bag Deactivation. Notice of Proposed Rulemaking. *Federal Register* **62** (3): 831-844.
48. Insurance Institute for Highway Safety (2005) Airbag Statistics. http://www.iihs.org/safety_facts/airbags/stats.htm
49. NHTSA (1997, November 21) Air Bag On-Off Switches. (Final Rule; Denial of Petition for Reconsideration) *Federal Register* **62** (225): 62405–62455.
50. NHTSA (2000, May 12) Final Rule: Federal Motor Vehicle Safety Standards: Occupant Crash Protection. *Federal Register* **65** (93): 30680-30770.
51. NHTSA (1997, March 19) Final Rule; Federal Motor Vehicle Safety Standards; Occupant Crash Protection. *Federal Register* **62** (53): 12960-12975.
52. U.S. Senate (1997, April 29) *Air Bags Safety*: Hearings before the Committee on Commerce, Science, and Transportation. One Hundred Fifth Congress, First Session.
53. Insurance Institute for Highway Safety (2004, March 6) Estimated Risk of Driver Death. *Status Report* **39**(3): 1-3.
54. NHTSA (1999) Traffic Safety Facts 1998 – Occupant Protection. Washington, D.C.
55. Air Bag & Seat Belt Safety Campaign (2000, April) A Powerful Partnership: Saving Lives and Protecting Futures. brochure, National Safety Council, Washington, D.C.
56. National Safety Council (2005, August 18), New Study Shows Dramatic Shift of Children to Back Seat. Press Release.
57. Insurance Institute for Highway Safety (2005) Airbag Statistics. http://www.iihs.org/safety_facts/airbags/stats.htm
58. National Society of Professional Engineers (2006) NSPE Code of Ethics for Engineers. <http://www.nspe.org/ethics/eh1-code.asp>