

Validating analytical judgments: the case of the airbag's lifesaving effectiveness

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Abstract

Based primarily on experimental testing and engineering judgment, early evaluations of airbags made variable predictions of their lifesaving benefits. The official estimates of the US government from 1977 to 1987 were that between 6000 and 9000 lives could be saved each year if all passenger cars were equipped with full-front airbags. Now, over a decade later, extensive real-world crash experience in the US has been analyzed to validate early predictions. Lifesaving estimates have been revised downward and the official US government position in 1997 was that, overall, approximately 3000 lives will be saved each year when the vehicle fleet is fully-equipped with frontal airbags. This article explores the reasons for poor validity of early lifesaving forecasts for airbags. We found that airbag effectiveness for unbelted adult occupants was overestimated, the number of adult motorists who would wear safety belts was underestimated, and that early analyses generally did not adequately address heterogeneity in the vehicle fleet or people. For each source of error, we discuss why technical specialists may have erred and what lessons can be gleaned from this case study in validation. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Although many people think that airbag technology is relatively new, engineers began developing and testing airbags in automobiles in the late 1940s. Airbags first appeared in commercial passenger vehicles in 1971 when Ford manufactured 831 Mercury models with driver-side frontal airbags. The largest early commercial offering of frontal airbags occurred in 1974–1976 when General Motors sold frontal airbags as an optional equipment on approximately 10 000 luxury models. However, no manufacturer offered airbags in the US between 1976 and 1984 when Mercedes-Benz offered them as an option [1]. Manufacturers considered airbags to be more expensive and less effective than other lifesaving technologies (particularly safety belts when used), but engineers continued to refine the technology as regulators began to indicate preferences for passive restraints [2].

In 1984 the federal government mandated that some form of passive restraint be installed in all new vehicles [3]. Under a revised legislative mandate, airbags are now required standard equipment for all new passenger vehicles.

Over 70 million passenger vehicles, or about one-third of the entire fleet, had airbags in 1997 [4].

The 1984 decision to mandate airbags was supported by estimates of the costs and benefits of the technology. The process of evaluating the technology and mandating its installation in vehicles evolved over a period of 25 years. Early estimates of the lifesaving benefits were based primarily on experimental testing and engineering judgment.

When making predictions in the face of uncertainty, technical experts are prone to bias and overconfidence to varying degrees [5–7]. In this article, our objective is to determine whether similar validation problems plagued early predictions of airbag effectiveness in saving lives.

We begin by providing historical context for the airbag requirement and highlighting the variability in the published estimates of lifesaving benefits for airbags in Section 2. We then describe in Section 3 the model used to predict the lifesaving benefits of airbags and explore the evolution of estimates for the model inputs. Finally, in Section 4, we suggest lessons learned from this retrospective review of the process.

2. Background

In 1966, Congress authorized the Secretary of

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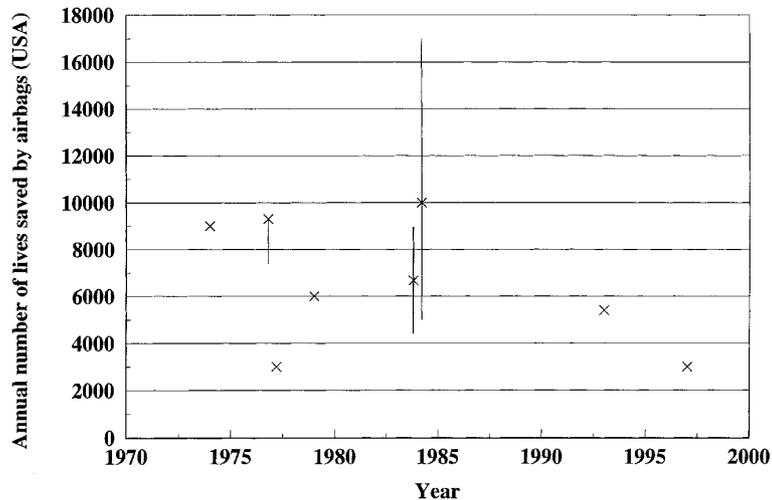


Fig. 1. Summary of national estimates of the annual lifesaving potential of airbags by source, assuming 100% penetration of the US vehicle fleet. Sources from L to R are: [29,8,8,9,12,13,37,16].

Transportation to protect the public from “unreasonable risk” of traffic accidents due to design, construction, or performance of motor vehicles [2]. The National Highway Traffic Safety Administration (NHTSA) proposed Federal Motor Vehicle Safety Standard 208 (FMVSS208) under this authority in 1968. FMVSS208 requires manufacturers to equip vehicles with occupant restraint systems. In 1972, with manual safety belt usage rates low (approximately 10%) and national annual occupant fatality counts exceeding 35 000, NHTSA issued its first passive restraint option as part of new requirements in FMVSS208 [2].

With belt usage rates remaining low, in 1973 NHTSA required manufacturers to install an ignition interlock system that prevented the motor vehicle from starting if belts were not used. Although interlock systems served to convert active restraints (manual belts) into compulsory restraints, NHTSA imposed this requirement with little public education at a time when no state or federal safety belt use laws existed. Public irritation and outrage with the interlock devices led the Congress to void the ignition interlock requirement of FMVSS208 [2].

In late 1976, NHTSA proposed a voluntary airbag demonstration program involving 50 000–100 000 vehicles [2]. Manufacturers agreed to this plan but consumer advocates and insurers were disappointed. Ultimately, in 1977, NHTSA reversed itself and required that all new cars be equipped with passive restraints by 1983 [8]. This requirement was supported by the results of a cost–benefit analysis that suggested passive restraints (airbags or passive belts) could prevent on the order of 6000 fatalities (with driver-only airbags) to 9000 fatalities (with full-front airbags) each year. In the same rulemaking, General Motors provided comments that suggested a very different estimate of less than 3000 lives saved by full-front airbags ([8], p. 34 292). Two years later, Huelke et al. [9] produced an estimate of approximately 6000 lives saved by full-front airbags.

The 1977 rule never took effect because NHTSA

rescinded it in 1981 [10]. This decision followed hard times for the industry, manufacturers’ concerns about dangers of airbags to out-of-position occupants (primarily small children), and a major change in the political climate to one that favored deregulation [1]. In 1983, when the insurance industry challenged NHTSA’s decision, the Supreme Court ruled that the rescission was “arbitrary and capricious,” made favorable comments about airbags, and remanded the issue to the agency for further consideration [11].

Consequently, NHTSA took up the passive restraint issue again in 1984. The final rule required manufacturers to install passive restraints (in 10% of 1987 models, 25% of 1988 models, 40% of 1989 models, and 100% of all 1990 and later models), unless two-thirds of the US population became subject to mandatory safety belt laws by 1 April 1989 [3]. This decision was also based on a NHTSA analysis that suggested passive restraints would save approximately 6000–9000 lives per year [12]. Around the same time, Graham and Henrion [13] performed a probabilistic analysis based on expert judgments and offered a median prediction that mandatory airbags would save approximately 10 000 lives per year (with an 80% credible range of 5000–17 000 lives saved per year).

Many manufacturers were planning to comply with the new rule by installing passive safety belts instead of airbags. In 1987, however, NHTSA amended FMVSS208 to allow exclusion of the passive-restraint requirement for the right-front passenger until 1 September 1993 if the vehicle contained a driver-side airbag which made this option more attractive to manufacturers [14]. Eventually, in the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA), Congress required that all new passenger vehicles (by 1 September 1997) and light trucks (by 1 September 1998) contain dual airbag systems and manual lap and shoulder belts, thereby removing the option to comply with passive belts.

As the number of airbags in the US fleet has increased, so has the amount of information about the effectiveness of the technology in the field, which allows re-evaluation of the lifesaving benefits of airbags. In 1993, Zador and Ciccone estimated that airbags would have saved approximately 5400 lives if fully-implemented in the 1990 vehicle fleet [37]. More recently, through 1 February 1998, NHTSA estimated that airbags had saved approximately 2840 lives on net (87% drivers and 13% passengers; 28% belted and 72% unbelted). At the same time, NHTSA counted 51 airbag-related deaths for children under age 12 (24% in rear-facing child seats, 76% not in such seats) and 40 for adults (10% passengers and 90% drivers, approximately 30% of which occurred in spite of the adult being restrained) [15]. NHTSA's most recent estimate of lifesaving benefits is that airbags will ultimately save approximately 3000 lives per year once fully-implemented in all passenger vehicles ([16], p. 16).

A recent analysis based on real-world experience found that frontal airbags compare favorably with other medical technologies based on their cost-effectiveness [17]. Nonetheless, airbags are expected to prevent far fewer fatalities than predicted at the time the technology was mandated and, as shown Fig. 1, predictions of lifesaving benefits have gradually dropped over time.

3. Predicting the lifesaving benefits of occupant restraints

To account for the differences between what was expected and what has been observed, we explore the model and inputs used to estimate the lifesaving benefits of airbags.

3.1. Models used to make national lifesaving estimates

Auto safety experts have long recognized that the lifesaving benefits of a restraint system (j) depend on its net effectiveness in reducing fatalities when used (e_j), the percentage of use (u_j), and the baseline number of fatalities (i.e. assuming no restraints) that the intervention can reduce (n_0). Effectiveness of occupant restraints is typically expressed as the net percentage reduction in fatalities for a restrained occupant compared to the situation when the occupant is unrestrained. Thus, the fatalities prevented by intervention j (F_j) compared to no restraints would be predicted as:

$$F_j = e_j \cdot u_j \cdot n_0. \quad (1)$$

Each of the variables in Eq. (1) depends on a number of factors. For example, vehicle restraint effectiveness (e_j) depends on the design of the technology and the different types of crashes experienced. The percentage of users (u_j) depends on the system requirements for action on the part of the user, the user's obligation to use the system (i.e. owing to the existence of a law or penalty), and/or the user's

perception of the potential benefits. Finally, the baseline number of fatalities (n_0) may depend on the number of cars on the road, the number of miles driven per car, the age and blood alcohol levels of drivers, the speed limit and other traffic laws, the enforcement of these laws, and other safety interventions [18].

When multiple interventions (or technologies or types of safety devices) are available, analysis of lives saved entails estimation of the incremental benefits of the different technologies. As manual safety belts are both cheaper and more effective than airbags (when used), belts represent the *status quo* or baseline technology. Considering only belts and airbags, we can partition members of the population into user groups according to safety belt and airbag use. Thus, members of the population are either users of airbags only ($u_{a,0}$), users of belts only ($u_{0,b}$), users of both ($u_{a,b}$), or of neither ($u_{0,0}$) such that $u_{a,0} + u_{0,b} + u_{a,b} + u_{0,0} = 1$. Assuming that e_b represents the net effectiveness of safety belts compared to no restraints, the lifesaving benefits attributable to belts (F_b) can be estimated as:

$$F_b = e_b \cdot (u_{0,b} + u_{a,b}) \cdot n_0. \quad (2)$$

Estimating the incremental reduction of fatalities associated with airbags is slightly more complicated. As airbag effectiveness depends on whether or not the occupant is wearing a safety belt, e_{a+b} is used to represent the combined effectiveness of the airbag plus belt compared to no restraints and e_a is used to represent the effectiveness of airbags for unbelted occupants. The relationship for the incremental reduction in fatalities attributed to the use of airbags (F_a) is:

$$F_a = e_b \cdot (e_a \cdot u_{a,0} + (e_{a+b} - e_b) \cdot u_{a,b}) \cdot n_0. \quad (3)$$

Viano [19] provides similar relationships and Thompson et al. [20] gave these same equations for the assumption of complete penetration of airbags in the vehicle fleet (i.e. 100% airbag use). Note that the models make a common engineering assumption that driver behavior is unaffected by the presence and use of restraints, an assumption that has been called into question [21]. The following three subsections review the evolution of the estimates of different model inputs for effectiveness, usage, and the number of fatalities, respectively.

3.2. Model inputs for effectiveness of restraints

3.2.1. Safety belts

By the late 1970s, numerous estimates of the effectiveness of safety belts were available based on their actual performance in crashes. Hurst [22] provided estimates of 83% reduction in fatalities for drivers and 80% for right-front passengers. Early NHTSA estimates ranged from 46 to 70% for manual lap belts and 57–59% for manual lap and shoulder belts [12]. A subsequent NHTSA analysis that controlled for crash severity estimated effectiveness to be 27% for manual lap belts and 43% for lap and shoulder belts

[23]. Another analysis adjusted for the distribution of vehicle damage and provided best estimates (and 90% confidence bounds) ranging from 39% (24–67%) to 55% (30–77%) using four different approaches [24]. In addition, NHTSA [12] reported estimates of belt effectiveness ranging from 20 to 77% based on experience in 11 other countries with mandatory safety belt use requirements. Ultimately, in its 1984 analysis of lifesaving benefits for airbags, NHTSA used a range of 30–50% for the effectiveness of safety belts [12]. Graham and Henrion [13] used effectiveness estimates of 40–75% for belts.

In the late 1980s, estimates of lap belt effectiveness dropped substantially to approximately 20%, while estimates of lap and shoulder belt effectiveness remained at approximately 40–45% [25–27]. Evans [27] indicated that the available data suggested that lap and shoulder belts are approximately 45% effective in reducing fatalities, an estimate that is still used by NHTSA [16,28].

3.2.2. Airbags for belted and for unbelted front-seat occupants

The earliest estimates of airbag effectiveness for reducing fatalities were based on mathematical models of the experience of the 831 Ford Mercury models that were equipped with airbags in 1971. These estimates suggested that airbags alone reduced the risk of fatalities by 27% and that belts (when used alone) were much more effective than airbags alone. In 1974, NHTSA noted that airbags were most effective for frontal crashes (particularly for impacts at less than 35 mph), and that they were less effective in side, rollover, and rear end impacts [29]. Effectiveness estimates for frontal crashes were based on experimental crash tests and combined with estimates for nonfrontal crashes using engineering judgment and information about the proportions of different types of impacts to assess overall effectiveness. NHTSA estimated airbags to be 32% effective for unbelted occupants and airbags plus lap belts to be 45% effective in reducing fatalities [29]. These estimates were much higher than an estimate of 17% that Wilson and Savage [30] offered based on having four expert engineers evaluate 706 fatal crashes and make judgments about whether or not airbags might have prevented the fatality.

Anticipated effectiveness of airbags increased in 1976 with the higher levels of effectiveness for safety belts, and as limited evidence suggested that airbags could be even more protective as airbag systems capable of restraining occupants in 40–45 mph frontal crashes had been designed. In 1977, NHTSA's estimates of effectiveness increased by 25% for airbags alone (from 32 to 40% effective) and by 40% for airbags plus lap belts (from 45 to 66%). These higher effectiveness estimates "were based on accident data for belted and unbelted occupants, laboratory results, some favorable observed outcomes associated with airbag-equipped vehicles, and engineering judgment" ([12], IV-39). The increase occurred in part owing to the speculative assumption that airbags would be 10% effective in rear

impact crashes, a situation in which airbags were not designed to deploy.

Huelke et al. [9] assessed 101 post-crash situations (primarily high-speed crashes in rural areas, conditions that tend to understate effectiveness) and used judgment to estimate effectiveness of safety belts and airbags for these crashes. In general, their estimates of effectiveness (23–27% for airbags alone and 33–35% for airbags plus lap belts) were much lower than NHTSA's estimates. This led them to conclude: "NHTSA's fatality reduction estimates are excessively high and overly optimistic" ([9], p. 1).

By the late 1970's, NHTSA's estimates of airbag effectiveness were influenced by the experience from General Motors' 1974–1976 airbag fleet ([12], p. IV-38). These limited field data yielded airbag effectiveness estimates for unbelted occupants ranging from 9 to 54% [31–33]. By 1984 the empirical estimates based on the GM fleet had dropped to 0% (90% confidence interval of –70–+46%), but at that point NHTSA largely discounted them because they lacked statistical significance [12].

Given diverse evidence ranging from high airbag effectiveness rates in controlled crash tests and low empirical estimates from the test fleet, in 1984 NHTSA characterized its effectiveness estimates as ranges: 20–40% for airbags alone and 40–55% for airbags and belts combined [12]. These ranges reflected diverse opinions within the agency about the importance of direction of impact and fatality mechanisms that would not be affected by airbags (e.g., ejection, intrusion, secondary impacts) [34–36]. Graham and Henrion [13] elicited slightly higher effectiveness estimates from their interviews with experts: 25–40% for airbags alone and 42–75% for airbags plus belts. Graham and Henrion [13] indicated that benefit estimates would vary widely among drivers according to variability in exposure, but they did not discuss the possibility that airbags would kill people as well as save lives. Several years later, Evans [27] projected that effectiveness for airbags would be approximately $18 \pm 4\%$ for unbelted drivers and $13 \pm 4\%$ for unbelted front-right passengers based on the available safety belt effectiveness data and assumptions about when airbags would be effective.

As field data became available in the early 1990s, estimates of airbag effectiveness dropped into the range of 14–22% for unbelted drivers and 9–17% for unbelted right-front passenger [37,38]. The most recent estimates of airbag effectiveness suggest that airbags are approximately 14% effective at reducing fatalities for *unbelted* drivers and right-front passengers over age 12, and 9% effective at reducing fatalities for *belted* drivers and right-front passengers over age 12 [39–41]. Part of this decrease is explained by lower levels of effectiveness than expected in partially frontal crashes (i.e. when the occupant trajectory is not directly into the airbag) [39,42]. Further, airbags appear to have a lower net effectiveness for the elderly than for younger adults and to cause so many fatal injuries to children that

Table 1
Number of states passing safety belt use laws by calendar year and type of law [4]

Year	Primary ^a	Secondary ^a	Total
1984	1		1
1985	3	3	7
1986	5	10	22
1987		7	29
1988	1	1	31
1989		2	33
1990	1	2	36
1991		3	39
1992		2	41
1993		2	43
1994		4	47
1995		2	49
Total	11	38	49

^a Primary laws allow authorities to stop and cite drivers due to lack of restraint use, while secondary laws only allow authorities to cite drivers for lack of restraint use when they are stopped for some other violation.

they have an overall negative impact on them with estimates extending from – 21 to – 88% [39–41].

Airbag effectiveness estimates are summarized in Fig. 2. Early estimates of effectiveness were for passenger cars; little experimental work or analysis was done to estimate effectiveness in other types of vehicles such as light trucks and vans. Since the early 1990s, data have become available for light trucks that suggest approximately 60% effectiveness for manual lap and shoulder belts, 10% for airbags alone, and 64% for an airbag plus lap/shoulder belt [28].

3.3. Model inputs for usage rates

3.3.1. Safety belts

In the 1970s, safety belt usage rates were estimated to be approximately 10–20% [12] and this relatively low rate undermined the lifesaving benefits of safety belts. In 1984, NHTSA estimated that between 11 and 14% of the population wore belts and used an estimate of 12.5% when it computed that airbags could save approximately 9000 lives per year [12]. The analysis did not adjust for possible future changes in belt use, which appeared to be declining at the time. Graham and Henrion [13] similarly indicated that belt usage rates declined from over 20% in the early 1970s to approximately 10% in 1980. The experts they interviewed estimated belt use in crashes at the time to be between 5 and 15% (90% credibility interval).

NHTSA also estimated that if all states enacted mandatory belt use laws, then 40–70% of the population would wear belts based on the experience in Canada and Australia [12]. The experts interviewed by Graham and Henrion [13] estimated a median compliance rate of 50% if mandatory belt use laws were passed, with an 80% credibility interval of approximately 25–70%. Notably, one of the five experts

refused to give an estimate because he believed that the probability of widespread adoption of belt use laws in the US was essentially zero.

NHTSA's 1984 regulation created incentives for manufacturers to promote the establishment of mandatory safety belt use laws because the requirement for passive restraints would be repealed if enough states passed laws by a certain date. Since 1984, when New York adopted the first mandatory belt use law, the number of states with mandatory belt use laws has continued to grow (see Table 1). Perhaps a direct result of the 1984 regulation [1], these laws are highly variable in their requirements and enforcement. Over 75% of them permit only secondary enforcement (i.e. authorities may only ticket drivers that are stopped for other violations), with the remainder permitting more effective primary enforcement (i.e. authorities can stop the driver due to lack of restraint use).

Despite weak laws in many states, rates of belt use have increased since 1984. Fig. 3 shows the belt use percentages for front-seat occupants involved in fatal crashes and for front-seat occupants involved in crashes with a front-seat fatality that are reported to NHTSA's Fatality Analysis Reporting System (FARS) [43]. In this data collection system, unbelted vehicle occupants are believed to be over-represented, because some people who wear belts are saved by them and hence are excluded from the database. Roadside observations (also shown in Fig. 3) indicate higher rates of safety belt use. These observations suggest that approximately 68% of Americans now wear belts, the official point estimate used by NHTSA in its 1997 estimate of the lifesaving benefits of airbags [16].

3.3.2. Airbags

As airbags were designed as a passive technology, usage rates should be close to 100% once bags are fully-implemented in the fleet. In 1984, NHTSA assumed a 98% "readiness factor" for airbags, allowing for occasional failure to replace or repair an airbag after an earlier deployment, for unreliability of the system (i.e. a rare failure of the mechanical system), and for intentional disablement of the system [12]. Graham and Henrion [13] assumed 100% usage of airbags. Currently, little information exists about actual "readiness" of airbags, although the assumption of 98–100% seemed reasonable until recent federal regulations allowed eligible motorists to disable their airbag systems or install manual on–off switches [16,44]. It is unknown that what percent of airbags may ultimately be disabled (either temporarily or permanently), although some have speculated the percentage could be as high as 20% [45]. This may lead to an increase in net benefits associated with airbags if the choice prevents people who would otherwise be endangered by them from being killed. However, the option to disable could also decrease the benefits if airbags become unavailable to vehicle occupants that could be saved by them.

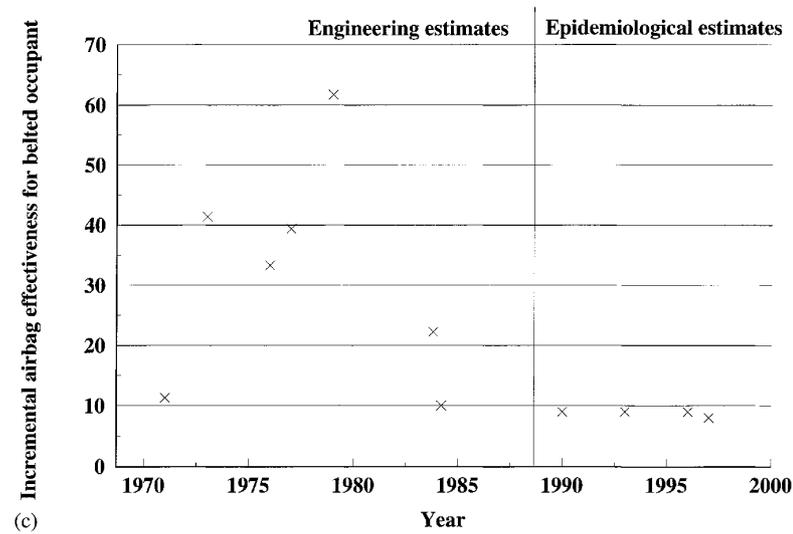
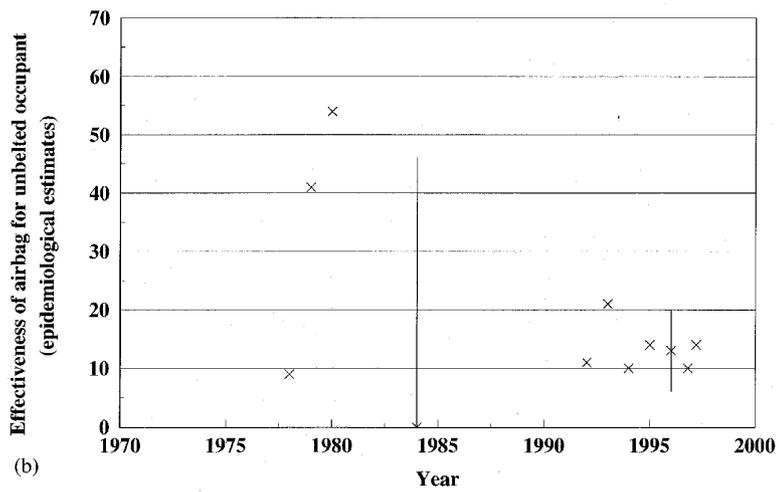
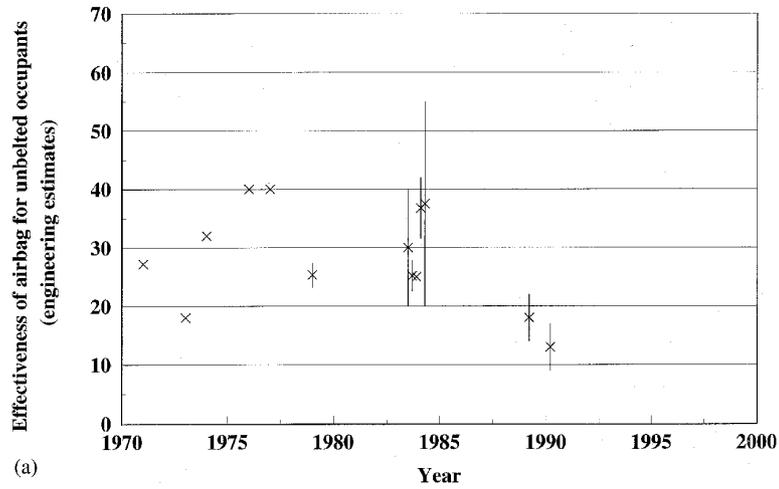


Fig. 2. Effectiveness estimates for airbags. Sources for 2(a) from L to R are: [57,30,29,2,8,9,12,34,35,36,13,27 (for drivers), 27 (for front-right passengers)]. Sources for 2(b) from L to R are: [31,32,33,12,39,37,42,38,16,40]. Sources for 2(c) from L to R are: [57,30,2,8,9,13,12,27,37,39,41].

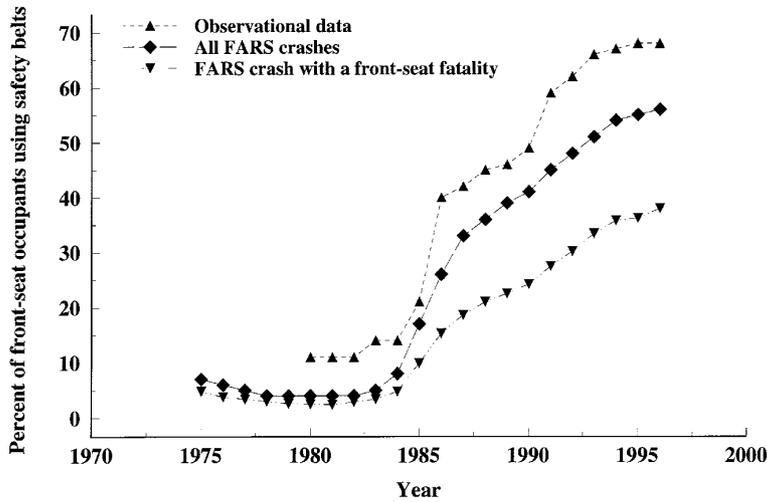


Fig. 3. Safety belt usage rates for front-seat occupants. Observational data from [56,55] and FARS data from [43].

3.4. Model inputs for the baseline number of fatalities with no restraints

In 1984, NHTSA observed that the annual number of front-seat fatalities reported to FARS had been relatively constant since 1975. The apparent stability of this number is remarkable because it masks the large increase in vehicles and miles driven per capita and the large decreases in fatality rates per mile of travel [46]. With no reason to predict otherwise, the agency forecasted 24 600 front-seat fatalities in passenger cars would occur each year in the absence of regulatory action ([12], p. VI-5). Graham and Henrion [13] used an assumption of 27 000 front-seat fatalities in passenger cars each year.

By focusing only on passenger cars, the estimates of life-saving did not explicitly account for other types of passenger vehicles such as light trucks. However, as passenger cars

dominated the passenger vehicle fleet at the time, this assumption was not recognized as a potential source of underestimation of the benefits of airbags.

Two important changes have occurred since then. First, while the numbers of front-seat fatalities in passenger vehicles has continued to remain relatively constant, it has declined for passenger cars and increased for light trucks as the relative popularity of light trucks has increased (Fig. 4). Second, the substantial growth in the safety belt use and partial penetration of airbags into the vehicle fleet means that these FARS data do not show people whose lives were saved by the interventions. It is incorrect not to include the people who were saved in the baseline number of people who could be saved (n_0) by the interventions. The adjusted numbers of fatalities based on current estimates of usage and effectiveness of the interventions are shown in Fig. 5.

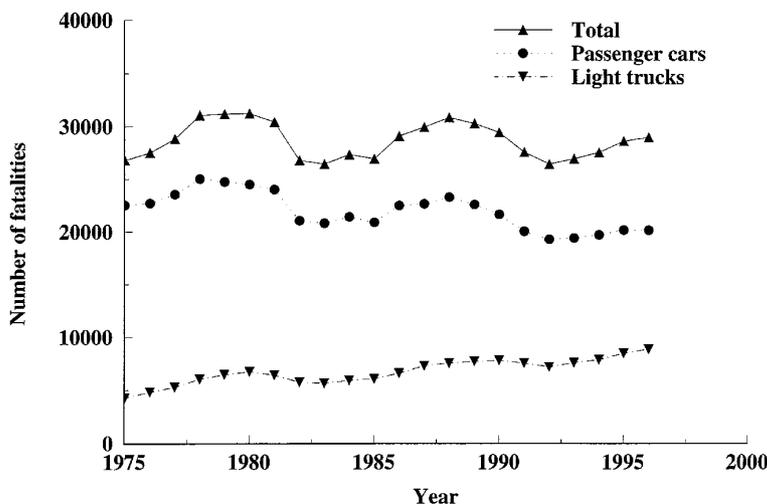


Fig. 4. Number of front-seat occupant fatalities in the US for passenger cars and light trucks. Source: [43].

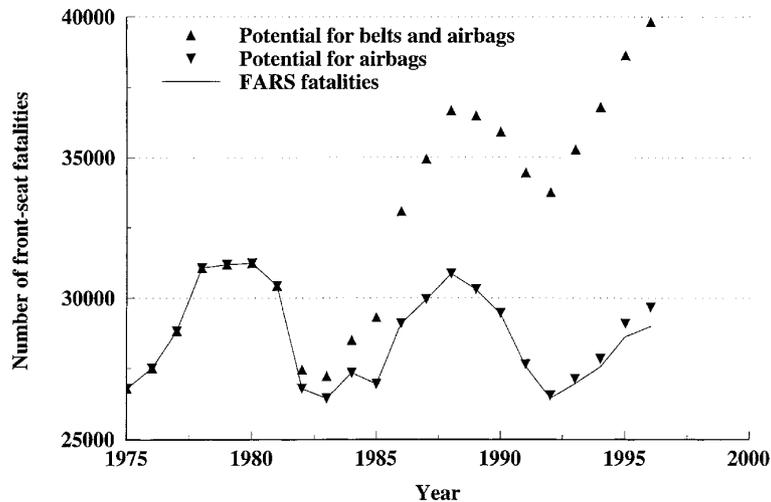


Fig. 5. Number of front-seat fatalities in passenger cars and light trucks corrected for safety belt use and airbag penetration. Source: [43].

4. Discussion of errors in judgment

We discuss two significant sources of error in lifesaving estimates. The order of discussion reflects the relative importance of the errors in distorting national estimates.

4.1. Overestimation of the effectiveness of airbags for unbelted individuals

As shown in Fig. 2, early estimates of effectiveness for airbags alone (i.e. for unbelted individuals) were much higher than current estimates. The drop from approximately 30–10% for unbelted occupant effectiveness accounts for almost all of the decrease in the lifesaving estimates (i.e. this change alone reduces the lifesaving estimates from 6000 to 9000 down to the 2000–3000 range). A number of factors contributed to the overestimation of effectiveness.

First, there was little acknowledgement that airbags could be the cause of fatalities, even though the device adds energy into the crash and its injury-inducing potential had been demonstrated as noted by NHTSA in 1984 ([12], p. IV-75). NHTSA did not produce a numerical estimate of the number of fatal injuries that could be caused by airbags.

Second, early effectiveness estimates were applied uniformly to all occupants, regardless of age, gender, physical stature, or health status. There was an implied assumption that designing airbags to protect unbelted 50th percentile adult men (in this case considered the “most-sensitive” individuals) would yield systems that protected all members of the population equally well. Consistent with this assumption, NHTSA’s compliance test incorporated dummies equivalent to unbelted adult men in the 50th-percentile of height and weight. Yet field evidence now suggests that current airbags are not very effective for some members of the population (e.g., the elderly) and that children in the front seat are particularly at risk. By focusing on only one segment of the population, the analysis

also missed the changing dynamics of the driver population (i.e. growth in the proportion of women and elderly front-seat occupants) [43].

Third, in 1984 NHTSA heard numerous concerns from automobile manufacturers that airbag systems might have to be “over designed” to meet the 30 mph compliance test due (i.e. to account for variability in vehicles and occupant positioning) [12]. For example, General Motors suggested a modified requirement that it proposed could result in comparable or greater safety benefits and that compensations made to account for variability and practicality constraints might be “contrary to the need for safety” ([12], p. III-46, III-52 to III-55). However, insurance companies and others disagreed with the premise held by manufacturers that an unbelted compliance test would induce risky over design. Instead, these other comments suggested that “over design is not only reasonable, but is a standard industry practice” ([12], p. III-61), a position that NHTSA took in the 1984 regulation ([12], p. III-69). In 1997, NHTSA ultimately changed the airbag compliance testing requirements to facilitate efforts to make airbags less aggressive (i.e. to depower them) [44]. Thus, retrospective analysis suggests that engineers recognized the trade-offs associated with designing airbags that were aggressive enough to protect the target population and the hazards to other members of the population. Nonetheless, it appears that they were ineffective in communicating these trade-offs to policy makers or that policy makers were unable to resolve these concerns.

Fourth, the experimental crash tests with dummies and occupants in proper seating positions provided little information about how airbags would perform for out-of-position occupants and in offset (or partially frontal) impacts. With respect to the compliance part of the standard, the Automobile Importers of America submitted comments to NHTSA that questioned the adequacy of the test dummies for predicting real-world human response to the same crash

forces ([12], p. III-49). Variability in the test procedures suggested that effectiveness would vary according to dummy positioning (e.g., a slight change in the placement of the passenger right foot or in the method of applying the force used in positioning the upper torso in the seat produced significant differences in the results). Nonetheless, the linkage between occupant positioning and estimates of airbag effectiveness were not directly made and, thus, estimates of effectiveness were not reduced to reflect this variability. Further, although engineers in the 1970s were concerned about the lack of effectiveness for out-of-position occupants, the expectation that occupants would be in position was not consistent with low expectations for belt use (as belts serve as a primary mechanism to keep occupants optimally positioned).

Fifth, the experimental crash tests with dummies and occupants in proper seating positions provided little information about how airbags would perform for different size occupants, specifically children. Engineers recognized the hazards that airbags could pose to children in the early 1970s (as reviewed by Mertz and Marquardt [47]). In 1980, the effects of airbags on children were discussed at a national meeting. Montalvo [48] estimated that 51 of the 149 expected unrestrained small children (infants through age four) (per million vehicle years in the front-seat would be close to the instrument panel and the airbag at the time of collision, but did not suggest what effects might result. Engineers at Honda reported on their tests of all three mounting designs of passenger airbag systems (low, top, and high) and concluded based on their results that “an unrestrained child occupant cannot be allowed to ride in the front seat” (Takeda and Kobayashi [49], p. 331). In contrast, NHTSA’s analysis suggested that it would be unlikely that children would be put at risk by an airbag, and that it was much more likely that children would be protected by airbags [50]. Their analysis assumed that restrained children would be at the instrument panel relatively infrequently at the time of airbag deployment and that greater use of secured child safety seats would further reduce the interactions that children would have with airbags. This view was supported by another report released around the same time which clearly demonstrated NHTSA’s expectation that manufacturers would fix the problem of children being hurt by airbags ([33], p. 75). In 1984, NHTSA minimized the potential that airbags might injure children, by arguing that child safety seats and manufacturing solutions would solve the problem ([12], p. III-10–III-12). Although NHTSA stated that “a small number of children could in fact be at greater risk from the airbag induced trauma than that from the effects of the crash itself,” this problem was portrayed as a small price and a technologically-solvable problem ([12], p. III-8–III-10).

Remarkably, with respect to rear-facing infant safety seats, NHTSA was aware of the use of child safety seats in the front seats of vehicles as early as 1984 ([12], p. VIII-11). However, the potentially deadly interaction between

airbags and rear-facing infant seats was not widely recognized until the early 1990s, when car manufacturers began adding warnings that such seats should not be placed in a front of an airbag. Although fatal interactions between infants and airbags could perhaps have been predicted and avoided with a strong educational message, the first such death occurred in July 1995 [51] and there are now at least 12 such deaths documented in the US [15].

In addition, older children (ages five through nine) whose deaths have been attributed to airbags were found to be unbelted or wearing only the lap belt and not the shoulder belt. This group of vulnerable children was similarly not anticipated by experts.

4.2. Underestimation of the growth in belt usage

Although experts recognized in 1984 that seat belt use could increase, particularly with the implementation of mandatory belt use laws, the estimates of lives saved by airbags were made based on the assumption that seat belt usage rates would remain low. Predicting the growth in safety belt usage (from 12.5 to 68%) would have dropped the lifesaving estimates into the approximately 3000–5000 range. Now that all states (except New Hampshire) have mandatory laws, the current belt use rates observed are consistent with the high end of the estimates offered by the behavioral experts [13]. Given the earlier experience with the ignition interlocks and the ineffectiveness of belt-use education, the experts did not expect increased belt use in the US [12,13].

The rescission provision in the NHTSA’s 1984 passive restraint rule played an important role in stimulating vehicle manufacturers to lobby for passage of mandatory belt use laws. Yet the same provision created incentives for airbag advocates to lobby for weak laws (i.e. low fines or the use of secondary enforcement) so that new state mandatory belt use laws would not lead to rescission of the passive restraint requirement [1]. Overall, the early estimates of safety belt usage appear to have been too low as belt acceptance and use have increased.

4.3. Unanticipated changes in the baseline number of fatalities with no restraints

The unanticipated growth in the popularity of light trucks in the fleet of passenger vehicles leads to two relevant sources of error. First, limiting the analysis to passenger cars leads to an underestimate of the total number of lives saved by airbags in passenger vehicles. This underestimation increases as the relative popularity of passenger cars decreases, as it has over time. Owing to this, NHTSA now estimates lifesaving benefits for passenger vehicles (by adding the results of Eq. (3) for passenger cars to the results of Eq. (3) for light trucks.). Second, as there has been a gradual increase in the popularity of light trucks and an offsetting decrease in passenger cars, the slightly lower effectiveness of airbags in light trucks implies a slightly

lower estimate of lifesaving overall, although this is not a significant error to date. Similarly, the failure to account for the role of airbags in maintaining the constant estimate of baseline fatalities in passenger vehicles (n_0) has not been a major source of error because of the relatively small penetration of airbags.

5. Conclusions

This article reviews the validity of early lifesaving forecasts for airbags. We found that airbag effectiveness for unbelted adult occupants was overestimated, the number of adult motorists who would wear safety belts was underestimated, and that the early analyses generally did not adequately address heterogeneity in the vehicle fleet or people. By revisiting this case, we add another set of evidence to the existing body of literature-related to the validity of technical judgments. Several clear themes that emerge from this analysis are likely to be widely applicable.

First, technologies often perform differently in controlled settings than in uncontrolled ones. When estimating benefits and risks for uncontrolled settings based on experimental data, it is critical to enlarge credibility intervals to account for unexpected happenings in the real-world. In the case of airbag effectiveness, even those early analyses that included uncertainty intervals did not include the ultimate truth within those uncertainty intervals. The degree of confidence placed in data derived from controlled crash tests was unwarranted.

Second, efforts should be made to quantify the potential risks of safety technologies, even though intuition may suggest that benefits will dwarf risks. The discipline of quantifying risks and subtracting them from benefits may lead to more realistic estimates of net effectiveness of safety technology. In the case of early airbag effectiveness estimates, we found no attempts to quantify the number of occupants who might be killed by adding deployment energy to crashes. Based on real-world crash experience, it is now apparent that the frequency of fatal airbag-induced injuries is not trivial and that net effectiveness is less than projected.

Third, designing technologies for the “sensitive subpopulation,” without adequate consideration of other subgroups, can lead to erroneous estimates of risk and benefit. The entire process of maximizing safety for high-risk groups assumes that the high-risk group has been properly identified and that the most-sensitive group for technological risk is the same as the high-risk group for benefit estimation. In the case of airbags, it is now apparent that the welfare of children (and possibly the elderly) were inadvertently short-changed by the preoccupation with protecting unbelted adult males (the presumed “sensitive group”).

Fourth, even when safety technologies are designed to be “passive,” it is critical to consider ways that human behavior can undermine effectiveness or create unanticipated risks.

NHTSA now recognizes, based on real-world injuries caused by airbags, that it is not sufficient to require airbags and expect that this “passive” device will work optimally. Through educational campaigns, NHTSA is (belatedly) encouraging drivers to buckle up properly and move the seat back to a position that allows at least 10 in. between the breastbone and the center of the steering wheel. Other messages, like the need to grip the steering wheel with hands in the 3 and 9 o’clock positions to avoid upper extremity injuries [52] and to measure the actual distance between the driver and the airbag [53] have also emerged. For children, the educational message is proper restraint in the rear seat. When behavioral complications are ignored, the so-called passive safety devices may have diminished effectiveness and unexpected risks.

Finally, estimates of risk and benefit should be subjected to refinement and validation over time as technology changes. Airbag technology is continually evolving as regulators, vehicle manufacturers, and suppliers respond to data gathered from real-world field experience. As refinements are made, estimates of benefit and risk should again be made, as NHTSA has done, allowing subsequent validation studies to be undertaken. A continuous process of safety improvement can be expected.

From a risk-analytic perspective, the airbag case study reveals how critical it is for engineers to consider variability in the population’s susceptibility to risk and benefit as well as the degree of uncertainty in estimates of risk and benefit [54]. Although such rigorous analytic discipline is difficult to accomplish, it can operate to reduce bias and overconfidence in estimation and thereby lead to technologies that maximize benefit, minimize risk, and foster warranted public confidence in technology. Ultimately, policy makers and other stakeholders in the regulatory process must refrain from myopic focus on one end of the spectrum of possibilities presented by analysts and they must address the differential impacts to various members of the population.

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