The Cost-effectiveness of Air Bags by Seating Position

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Context.—Motor vehicle crashes continue to cause significant mortality and morbidity in the United States. Installation of air bags in new passenger vehicles is a major initiative in the field of injury prevention.

Objective.—To assess the net health consequences and cost-effectiveness of driver's side and front passenger air bags from a societal perspective, taking into account the increased risk to children who occupy the front passenger seat and the diminished effectiveness for older adults.

Design.—A deterministic state transition model tracked a hypothetical cohort of new vehicles over a 20-year period for 3 strategies: (1) installation of safety belts, (2) installation of driver's side air bags in addition to safety belts, and (3) installation of front passenger air bags in addition to safety belts and driver's side air bags. Changes in health outcomes, valued in terms of quality-adjusted life-years (QALYs) and costs (in 1993 dollars), were projected following the recommendations of the Panel on Cost-effectiveness in Health and Medicine.

Participants.—US population-based and convenience sample data were used.

Main Outcome Measure.—Incremental cost-effectiveness ratios.

Results.—Safety belts are cost saving, even at 50% use. The addition of driver's side air bags to safety belts results in net health benefits at an incremental cost of $24 000 per QALY saved. The further addition of front passenger air bags results in an incremental net benefit at a higher incremental cost of $61 000 per QALY saved. Results were sensitive to the unit cost of air bag systems, their effectiveness, baseline fatality rates, the ratio of injuries to fatalities, and the real discount rate.

Conclusions.—Both air bag systems save life-years at costs that are comparable to many medical and public health practices. Immediate steps can be taken to enhance the cost-effectiveness of front passenger air bags, such as moving children to the rear seat.

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MOTOR VEHICLE crashes are a significant cause of mortality and morbidity in the United States. They are the leading cause of death among children and young adults and a major cause of brain and spinal cord injury.[1,2] In 1994, 20 647 drivers and 6491 front passengers suffered fatal injuries in crashes involving the 180 million passenger cars and light trucks registered in the United States.[3,4] In addition, nearly 1.5 million vehicle occupants experienced nonfatal injuries, of which 7% were severe enough to cause some degree of residual functional limitation 1 year after the crash.[5]

One of the recent responses to the crash-injury problem has been the installation of air bag systems in new motor vehicles. More than 56 million new vehicles were sold in the United States with a driver's side air bag system during model years 1989 through 1996; 27 million of these vehicles were also equipped with a front passenger air bag.[6] Dual air bags (ie, driver's side and front passenger) became required standard equipment in all new passenger cars sold in the United States beginning in 1997; all light trucks are required to have them beginning in 1998.[6] Although market penetration of air bags has been most rapid in the United States, air bags are also penetrating new vehicle markets in Europe and Asia without regulatory impetus.

An air bag system is composed of 3 components: an air bag module that houses the inflator and bag, crash sensors that measure deceleration and trigger deployment, and an electronic diagnostic unit that monitors the operation of the system. Current air bag systems are designed to inflate in frontal or front angle crashes, which account for approximately 65% of fatalities to front seat vehicle occupants.[4] The air bags deploy within about 0.05 second after the sensors detect a rate of deceleration equivalent to striking a brick wall at 10 to 15 mph. The deployed air bags begin to deflate 0.2 second following impact; once deployed, they must be replaced.

See also p 1437.

In the early 1980s, several economic evaluations reached conflicting conclusions about whether the additional effectiveness offered by air bags relative to safety belts would justify the costs of air bags.[7,8] The benefit and cost estimates in these early studies were based primarily on expert judgment and experimental testing because few real-world data on air bags were available. Since 1989, the database on air bag performance has expanded rapidly. It has been estimated that approximately 782 000 air bag deployments occurred in the United States from 1989 to 1995[9] at a deployment rate of approximately 4 inflations per 1000 vehicle-years.[10]

Capitalizing on the availability of real-world data, recent studies have evaluated the effectiveness of the air bag systems installed in US vehicles.[6,9,11-15] These studies show that air bag deployments reduce fatal injuries to front seat occupants in frontal crashes. The National Highway Traffic Safety Administration (NHTSA) estimated that between 1989 and February 15, 1997, driver's side and front passenger air bags saved 1639 and 189 lives, respectively.[16]

Some evidence suggests that air bags cause injuries. Air bags must deploy within milliseconds of the beginning of a crash and at very high speeds to protect occupants. The energy produced by the rapidly deploying air bag has the potential to injure someone whose hands, arms, chest, head, or face are in the path of the air bag while it deploys. Although most air bag–induced injuries have been minor, serious ones increasingly are reported. Twenty-one driver fatalities and 2 adult front passenger fatalities, mostly

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among elderly, short women, have occurred because of air bag deployments in various crash situations.[16] Most disturbing is the mounting evidence from in-depth crash investigations that children in the front passenger seat are encountering unique hazards in their interactions with air bags.[17-19] Front passenger air bags have been responsible for 38 child fatalities in crash situations that would not likely have been fatal in the absence of the air bag deployment.[16,18]

The objective of our study is to evaluate the costs, benefits, and cost-effectiveness of US air bag systems compared with manual safety belt systems. We specifically evaluate the incremental benefits, risks, and costs of the addition of driver's side air bags to the familiar manual safety belt systems and of front passenger air bags to driver's side air bags. We also compare the cost-effectiveness ratios for air bags with ratios for a variety of common medical and public health interventions. We emphasize how the cost-effectiveness ratios for air bags might change if federal agencies, state governments, manufacturers, or citizens implement various behavioral policies or technological innovations currently under consideration.

METHODS

Cost-effectiveness Analysis

The method of cost-effectiveness analysis used here, particularly our reference case analysis, is consistent with the consensus recommendations of the Panel on Cost-effectiveness in Health and Medicine commissioned by the US Department of Health and Human Services.[20,21] Intended to inform resource allocation decisions at the societal level, the analysis adopts the societal perspective and incorporates information on all risks, costs, and benefits resulting from these strategies, regardless of who incurs them. The reference case is defined by a standard set of methods and assumptions and serves to facilitate valid comparison of cost-effectiveness ratios across studies of diverse public health and clinical interventions.

A cost-effectiveness analysis evaluates a given health intervention through the use of a cost-effectiveness ratio. In this ratio, all changes in resource use (relative to a stated alternative and valued in monetary terms) are captured in the numerator, and all health effects of an intervention (relative to the alternative) are captured in the denominator. Thus, the productivity costs of morbidity and functional limitation are incorporated into the denominator.[20] The reference case incorporates both mortality and morbidity consequences in the denominator using the single measure of quality-adjusted life-years (QALYs).

A deterministic state transition model using an Excel spreadsheet[22] was devised to track a hypothetical fleet of 10 million new vehicles for a period of 20 years. The number of vehicles in the fleet decreases as they are scrapped because of normal use and accident-related damage. The overall normal vehicle scrappage rates were assumed to be 15% at year 5, 50% at year 10, 65% at year 15, and 100% at year 20 (the maximum vehicle life is assumed to be 20 years).[23] The number of air bag deployments in a year is estimated by multiplying the number of vehicles in the fleet for that year by the deployment rate (ie, deployments per vehicle-year). If the cost of replacement approaches the residual value of the damaged vehicle, then the deployed air bags are not replaced and the vehicle is assumed to be scrapped. Based on limited experience, the replacement rates for air bags are 70% during year 1, 59% during year 2, 56% during year 3, 40% during year 4, 21% during year 5, 10% during years 6 through 10, and 0% during years 11 through 20.[10]

Based on the profile of vehicles in the fleet over its lifetime, we project changes in resource costs and health outcomes for 3 strategies: (1) installation of manual lap and shoulder belt systems as the status quo, (2) installation of driver's side air bags in addition to safety belts, and (3) installation of front passenger air bags in addition to safety belts and driver's side air bags. The results are presented as incremental cost-effectiveness ratios with health effects expressed in QALYs and costs expressed in 1993 US dollars. All future health effects and costs (incurred beyond the initial year of the intervention in the model) were discounted using a 3% annual discount rate, which is intended to reflect a real rate of time preference or a real rate of return on alternative investment opportunities. The cost-effectiveness estimates are independent of the size of the fleet modeled.

The target population of the present study is drivers or front passengers of any age in the United States. The literature suggests differences in the effectiveness of air bags for distinct subgroups in the population (ie, for children younger than 10 years, adults aged between 10 and 64 years, and adults older than 65 years) as reviewed below. We assume that owners will not disarm their air bags and that driver behavior is not affected by the presence of an air bag. The number of fatalities avoided for a subgroup is estimated by multiplying the number of vehicles, the baseline fatality rate, the percentage of the population involved in crashes represented by the subgroup, and the effectiveness of the intervention for reducing fatalities for the subgroup. Similarly, the number of nonfatal injuries avoided for a subgroup is estimated as the number of baseline fatalities for the subgroup multiplied by the ratio of injuries to fatalities and the effectiveness of the intervention for reducing injuries. The model estimates the installation, replacement, and maintenance costs and the medical and legal resources saved by an intervention as a function of the profile of vehicles in the fleet over its lifetime, the rates of air bag deployment and vehicle scrappage, and the numbers of fatalities and injuries. The model estimates changes in QALYs by combining the estimated numbers of fatalities and injuries avoided with weights that are generated by a Markov submodel using TreeAge[24] based on average health-related[25] and trauma-related[26] quality-of-life data.

To explore and validate the behavior of the model, we performed a global univariate sensitivity analysis that varied each model input by ±30%. Focused sensitivity analyses were then performed on the most uncertain input parameters to determine how much the cost-effectiveness ratios changed in response to plausible changes in their values. Reference case values and ranges for model inputs are listed in Table 1.[2-5,9,10,12,14,23,25-31]

Event Rates for Injuries and Fatalities

Rates of death and injury vary by seating position. In 1994, there were 115 driver fatalities per million vehicles compared with 36 front passenger fatalities per million vehicles.[3,4] The smaller rate of death in the right front seat reflects the lower rate of occupancy in this seating position. Among the fatally injured drivers in 1994, 16.2% were aged 65 years or older. Among the fatally injured front passengers, 5.3% were younger than 10 years, and 21.6% were aged 65 years or older.[4]

Crash-related injuries are typically classified by severity using the Association for the Advancement of Automotive Medicine's 6-point Abbreviated Injury Scale (AIS).[32] According to this scale, levels AIS 1 to AIS 6 correspond to progressively more life-threatening injuries. The most severe injury any individual suffers is normally referred to as the maximum AIS (MAIS). Since air bags have little net effectiveness on MAIS 1 injuries (as discussed below), they are not included in the analysis. In addition, most MAIS 6 injuries are fatal, and we assume they are counted among the fatalities. For each occupant killed in 1994, another 8.7 occupants suffered moderate to critical (MAIS 2-5) nonfatal injuries as defined by the 1990 version of the AIS.[3] Since we use the only injury cost estimates available in the literature and they refer to injuries coded

Table 1.—Reference Case Values and Ranges Used in Sensitivity Analysis

Variables	Baseline Value	Range	References
Event rates			
Fatality rate per million vehicle-years, No.			
Driver	115	80-149†	NHTSA[4]
Front passenger	36	25-47†	NHTSA[4]
Ratio of MAIS 2-5 injuries to fatalities, %	16.8	11.8-21.8†	NHTSA,[3] Garthe et al[27]
Air bag deployment rate per 1000 vehicle-years	4	2.8-5.2†	Ferguson et al[12]
Percent of MAIS 2-5 by			
MAIS 2	77.6	...	Segui-Gomez,[5] Garthe et al[27]
MAIS 3	18.6	...	Segui-Gomez,[5] Garthe et al[27]
MAIS 4	3.0	...	Segui-Gomez,[5] Garthe et al[27]
MAIS 5	0.8	...	Segui-Gomez,[5] Garthe et al[27]
Target population, %			
Drivers >64 y	16.2	...	NHTSA[4]
Front passengers <10 y	5.3	...	NHTSA[4]
Front passengers >65 y	21.6	...	NHTSA[4]
Intervention effectiveness rate			
Occupant seat belt use, %	50	...	Evans,[28] NHTSA[29]
Seatbelts, %	45	...	Evans,[28] NHTSA[29]
Air bags for adults 10-64 y, %	13	5-19	Ferguson,[9] Kahane[14]
Air bags for adults >64 y, %	5	0-19	Ferguson,[9] Kahane[14]
Air bags for children <10 y, %	−21	−88-0	Ferguson,[9] Kahane[14]
Costs, in 1993 dollars			
Air bag installation			
Driver's side	278	236-319	NHTSA[30]
Dual	410	356-464	NHTSA[30]
Air bag maintenance			
Driver's side	25	0-50	American Honda Motors Co[31]
Dual	50	0-100	American Honda Motors Co[31]
Air bag replacement‡			
Driver's side	664	240-1800	Werner and Sorenson[10]
Dual	1452	720-5435	Werner and Sorenson[10]
Fatality, total cost	99 992	69 994-129 990†	Blincoe[2]
Injury, lifetime cost			
MAIS 2	13 884	9718-18 049†	Blincoe,[2] Garthe et al[27]
MAIS 3	46 469	32 528-60 410†	Blincoe,[2] Garthe et al[27]
MAIS 4	137 116	95 981-178 251†	Blincoe,[2] Garthe et al[27]
MAIS 5	440 802	308 561-573 043†	Blincoe,[2] Garthe et al[27]
Quality-of-life weights			
Because of injury for			
MAIS 2	0.71	0.50-0.92†	Segui-Gomez,[5] AAMA,[23] MacKenzie et al[26]
MAIS 3	0.67	0.47-0.87†	Segui-Gomez,[5] AAMA,[23] MacKenzie et al[26]
MAIS 4	0.51	0.36-0.66†	Segui-Gomez,[5] AAMA,[23] MacKenzie et al[26]
MAIS 5	0.06	0.04-0.08†	Segui-Gomez,[5] AAMA,[23] MacKenzie et al[26]
For aging of general population§			
<45 y	1.0, 1.0	...	Fryback et al[25]
45-54 y	0.94, 0.90	...	Fryback et al[25]
55-64 y	0.87, 0.87	...	Fryback et al[25]
5-74 y	0.84, 0.83	...	Fryback et al[25]
75-85 y	0.84, 0.79	...	Fryback et al[25]
>85 y	0.82, 0.80	...	Fryback et al[25]

*MAIS indicates maximum Abbreviated Injury Scale; NHTSA, the National Highway Traffic Safety Administration; AAAM, the Association for the Advancement of Automotive Medicine; and ellipses, not applicable.
†Range reflects ±30% of base-case value.
‡See "Methods" section in text for the probabilities of air bag replacement as a function of vehicle age and vehicle survival data.
§These are age-specific weights from the time trade-off method for the general population for men and women from the Beaver Dam Health Outcomes Study.

according to the 1985 version of AIS, we adjusted this ratio of nonfatal injuries to fatalities to 16.8 using a recently suggested method[27] and distributed the cases by MAIS level (77.6% MAIS 2, 18.6% MAIS 3, 3% MAIS 4, and 0.8% MAIS 5).

Event rates of fatalities and injuries per vehicle-year for the reference case are based on the above data and are assumed to be constant from the point of vehicle purchase until the vehicle is scrapped. New cars are driven more than old cars, yet old cars tend to have more high-risk drivers than new cars. The sensitivity analyses relax our assumptions in both directions.

Effectiveness of Lap-Shoulder Belts

Lap-shoulder belt systems reduce the risk of fatality and serious injury (given a collision) by about 45% when used by drivers and front passengers.[14,28] For years voluntary rates of adult safety belt use were less than 20% in the United States[33]; consequently, 49 states adopted some form of mandatory safety belt use law for adults (all but New Hampshire).[6] All 50 states also have laws requiring young children to travel in proper restraint systems.[6] The laws covering the behavior of adults and children are not rigorously enforced by the police in most states, even though it has been demonstrated that restraint use rates depend on the amount and type of police enforcement.[34,35]

National estimates of belt use vary from 30% to 70%.[29] These estimates are known to be biased to unknown degrees by several sources of measurement error. The lower end of the range represents the rate of belt use among fatally injured occupants. The upper end of the range represents use among occupants who survive tow-away crashes and is probably an overestimate because crash survivors may be untruthful to police regarding actual use given current laws. Roadside observational surveys are the most accurate measure of actual behavior but are known to overestimate the belt use rate in crash situations. We assume the operative rate of safety belt use in the United States is 50% in crash situations.[14,30,36] In the sensitivity analysis we consider the implications of 100% belt use.

Effectiveness of Air Bags for Fatalities

Nationwide fatality and injury counts have not yet been influenced significantly by air bags because fewer than 30% of the vehicles on the road in 1995 were equipped with an air bag system. However, national databases with make, model, and type of crash information have been analyzed to assess the real-world performance of air bag systems.[6,9,11-15]

A 1995 study used vehicle registration data to compute overall driver fatality rates per 10 000 registered vehicles for vehicles with air bags and belts and for the same model vehicles with belts only.[11] The study reported driver fatality rates to be 16% lower than expected for vehicles with air bags and manual belts compared with vehicles with belts only.[11] The validity of this estimate depends on the assumptions that crash severities and safety belt use rates are comparable in the 2 fleets of vehicles. While these assumptions are reasonable, they cannot be verified rigorously with information in the Fatal Accident Reporting System (FARS), a national census of fatal motor vehicle crashes maintained by the NHTSA. An update of this study used more data and 2 different methods and reported 2 slightly lower effectiveness estimates of 14% and 15%.[13]

The largest air bag evaluation effort to date was based on FARS data for calendar years 1986 to 1996.[14] This analysis estimated air bag effectiveness in reducing driver fatalities using 2 methods. The first method, which compared the fatality ratios of drivers to passengers in cars with driver-only air bags to ratios associated with similar model cars with no air bags, led to an effectiveness estimate of 10%. The second method, which compared the ratio of fatalities in frontal to nonfrontal crashes for vehicles with air bags to the same ratio for vehicles with no air bags (based on the assumption that air bags are not effective in nonfrontal crashes), led to an effectiveness estimate of 12%. These estimates suggest that the presence of an air bag system reduces the driver's overall fatality risk (in all crashes) by about 11%.[14]

The 11% effectiveness estimate roughly comprises a 13% (95% confidence interval [CI], 6%-19%) reduction in fatality risk among unbelted drivers and a 9% (95% CI, 3%-15%) reduction in fatality risk among belted drivers.[14] Although the difference in effectiveness for unbelted and belted drivers is not statistically significant, the difference is consistent with the results from a similar study of the same data[9] and with expectations derived from biomechanical theory and experimental crash testing.[37]

The effectiveness information for front passenger air bags is more limited than for driver's side air bags because front passenger air bags entered the fleet several years later than driver's side air bags, and there is a much lower rate of occupancy in the front passenger seat.[9] Initial estimates using FARS data for 1992 to 1995 model vehicles suggested 18% fewer passenger deaths overall than expected in frontal crashes of vehicles with dual air bags compared with vehicles with driver-only air bags, or about an 11% effectiveness rate in all crashes.[12] The Kahane[14] analysis indicates that air bags reduce the fatality risk of front seat passengers older than 13 years by about 13%. In its review of the available studies, NHTSA found that the data suggest that driver's side and front passenger air bags appear to be equally effective for occupants aged 13 years and older.[6]

While front passenger air bags appear to decrease fatality risks for adults, evidence suggests that they increase fatality risk for passengers younger than 10 to 15 years.[13,14] The adverse effects of air bags on small children—particularly those who are unrestrained or improperly restrained and slide forward during precrash braking or those who are in rear-facing infant restraint devices—are increasingly documented and often occur in low- to moderate-severity crashes that may not have been fatal (or even injurious) in the absence of air bag deployment.[9,12,14,17,18]

For both driver's side and front passenger air bags we assumed effectiveness rates of 13% for occupants aged 10 to 64 years and 5% for occupants older than 65 years.[9] For front passenger air bags, we assumed an increase of 21% in fatalities and injuries for children younger than 10 years, even though this estimate is based on small counts of childhood fatalities and does not differ significantly from zero.[9] Larger estimates of increased risk to children aged 12 years and younger (28% and 88%) were reported by Kahane[14] using somewhat different data. Sensitivity analyses were performed on these key inputs to the model.

Effectiveness of Air Bags in Preventing Nonfatal Injuries

Air bags are designed to prevent head, face, and upper torso injuries but can also cause upper extremity, chest, and facial injuries. The challenge in air bag effectiveness research is to quantify the changes in magnitude of each type of injury by severity level.

The air bag's effectiveness in reducing serious injuries to the head, face, and upper torso in frontal crashes is statistically significant, has been confirmed in several studies, and is apparent for belted as well as unbelted drivers.[10,14,38] The precise magnitude of the effect is unknown, since estimates from the different studies vary considerably.

Injuries induced by air bag deployment are frequently reported,[10,39,40] with somewhat greater frequency among female drivers.[38] In a study of 2007 air bag deployments in the United States, 42% resulted in at least 1 such injury to a front seat occupant.[9] Of these air bag–induced injuries, 97% were minor (MAIS 1), composed primarily of head contusions and abrasions to the head, neck, face, and upper extremities. An additional 2% were moderate (MAIS 2) and included concussions and rib, sternum, and upper extremity fractures. Among the remaining severe injuries (MAIS 3+), heart lacerations, lung contusions, forearm fractures, and eye injuries were reported. Whether these injured occupants would have suffered more or less severe injuries in the absence of air bag deployments remains unclear.

For baseline values, we assume that air bags cause as many AIS 1 injuries as they prevent, and thus we focus on the more serious injuries (MAIS 2-5), which are expected to have a greater impact on quality-adjusted life expectancy and costs. We also make the assumption that air bags are as effective at reducing MAIS 2 to 5 injuries as they are at reducing fatalities, based on the evidence indicating reduced injuries to the head, face, and chest. However, this assumption will need to be replaced in the future with rigorous estimates derived from detailed studies of the severity distributions of nonfatal injuries in vehicles with and without air bags.

Costs

Like many injury-related preventive health interventions, the major resource investment occurs at the time of the factory installation of the belts and air bags. The factory installation costs for mass-produced manual lap and shoulder belts are assumed to be approximately $57 per

Table 2.—Reference Case Results*

Strategies	Total Net Cost (Includes Savings) per 10 Million Vehicles, in Millions, 1993 Dollars	Total Effectiveness per 10 Million Vehicles, QALYs	Incremental Cost per 10 Million Vehicles, in Millions, 1993 Dollars	Incremental Effectiveness per 10 Million Vehicles, QALYs	Cost-effectiveness Ratio, Incremental Dollars per Incremental QALY
Discounted results (3%)					
No air bags (manual lap-shoulder belts)	−1357†	219 629	...	...	...
Driver's side air bag (plus manual restraints)	853	312 735	2210	93 106	24 000
Dual air bag system (plus manual restraints)	2184	3 334 531	1331	21 796	61 000
Undiscounted results					
No air bags (manual lap-shoulder belts)	−1853†	479 431	...	...	...
Driver's side air bag (plus manual restraints)	210	683 821	2063	204 390	10 000
Dual air bag system (plus manual restraints)	1542	728 361	1332	44 541	30 000
Discounted results (5%)					
No air bags (manual lap-shoulder belts)	−1110†	145 234	...	...	...
Driver's side air bag (plus manual restraints)	1172	206 471	2282	61 237	37 000
Dual air bag system (plus manual restraints)	2502	221 104	1330	14 633	91 000

*QALYs indicates quality-adjusted life-years; ellipses, not applicable.
†Net costs are negative because savings exceed belt costs.

vehicle.[30,41] The air bag costs are assumed to be $278 for the driver's side air bag in the steering wheel and for the sensor and control unit and $410 for the dual air bag system.[30] The reported charge for air bag replacement after a crash ranges from $720 to $5435, with a central estimate for high-volume cars around $664 for the driver's side air bag and $1452 for dual air bags.[10] We further assume that air bags require a one-time maintenance check at 10 years (at least for air bags with electronic sensors) that will entail approximately 30 minutes of labor per air bag at a cost of $50 per hour of labor.[31] The costs of air bags (particularly for electronic sensors) may be declining, and thus we performed sensitivity analyses for these estimates.

Resources are consumed as a result of crash-related injuries and fatalities. The present value of lifetime injury-related costs are estimated to be an average of $99 992 per fatality and $27 057 per nonfatal MAIS 2 to 5 injury.[2,42] These figures include insurance administration and legal fees, court costs, and medical costs associated with emergency services, hospitalization, outpatient care, and rehabilitation. These costs are included as savings (ie, negative costs).

Health-Related Quality of Life

A Markov submodel was used to determine the appropriate weights for conversion of the estimated numbers of avoided fatalities and injuries to total QALYs saved for each subgroup of the population. Using data from US life tables and actuarial data on the age distribution of fatalities in motor vehicle crashes,[4] the Markov submodel estimates discounted life expectancy and quality-adjusted life expectancy. Although cost-effectiveness analyses have typically assumed that a life-year saved by an intervention is valued at 1.0 QALY, the Panel on Cost-effectiveness in Health and Medicine recommends, in the reference case, that life-years saved be adjusted to reflect the average health-related quality of life in the target population.[20,21] Lacking specific data on the health status of people in crashes, we used age- and sex-adjusted weights derived from the time trade-off estimates reported in the Beaver Dam Health Outcomes Study (BDHOS).[25] The BDHOS is an ongoing longitudinal cohort study of health status and health-related quality of life for a random sample of adults in a community population. We conservatively assumed that the quality weight for each year of life saved for those younger than 45 years was 1.0, largely because no quality-adjusted data were collected for this younger (and presumably healthier) age range. Discounted QALYs lost per fatality were estimated for an average adult aged between 10 and 65 years (ie, a 37-year-old), an average adult older than 65 years (ie, a 75-year-old), and an average child younger than 10 years (ie, a 5-year-old). We explored the impact of using an alternative health state classification system (ie, the National Center for Health Statistics' *Years of Healthy Life*[43]) in the sensitivity analysis. We also report results without adjusting for baseline population health-related quality of life (ie, assuming QALY weights of 1.0 per life-year).

To account for diminished health-related quality that results from crash-related injuries, we used quality weights associated with each MAIS injury as measured by the Functional Capacity Index (FCI).[26] The FCI weights represent rating scale preferences elicited from a convenience sample for injuries that result in functional limitations persisting longer than 1 year after injury, and they are not age or sex specific. Using data from the National Accident Sampling System's Crashworthiness Data System (NASS CDS) for 1994 and 1995 for those injuries that lead to some functional limitation, average residual quality weights of 0.71, 0.67, 0.51, and 0.06 were assigned to MAIS 2, MAIS 3, MAIS 4, and MAIS 5, respectively.[5,26] Because some MAIS 2 to 5 injuries are transient (ie, within 1 year the health state is restored to normal) and the model considers both persistent and nonpersistent injuries, these residual quality weights were multiplied by the proportions of MAIS 2, MAIS 3, MAIS 4, and MAIS 5 persistent injuries (37.1%, 47.7%, 14.9%, and 85.7%, respectively) and added to the complementary proportions of nonpersistent injuries that were assigned QALY weights of 1.0. This resulted in residual quality weights for all injuries of 0.89 (MAIS 2), 0.84 (MAIS 3), 0.93 (MAIS 4), and 0.19 (MAIS 5).[5] The relatively small percentage of MAIS 4 injuries that result in functional deficits lasting longer than 1 year reduces the relative significance of these injuries.

The final QALY weight for the remaining life expectancy of an injured person was then obtained by multiplying the injury-specific QALY weight to the corresponding age-specific baseline QALY weight for use in the Markov submodel. The QALYs saved by avoiding injuries are then estimated by finding the difference in QALYs between injured individuals and noninjured individuals at the baseline health-related quality of life.

RESULTS

The reference case results are shown in Table 2. Safety belts alone are cost saving, even at a 50% usage rate. The incremental cost-effectiveness of the addition of a driver's side air bag was estimated to be $24 000 per QALY saved. The incremental cost-effectiveness of the addition of the dual air bag system (front passenger plus driver's side air bags) relative to the driver-only air bag was $61 000 per QALY saved. The dual air bag strategy was less attractive because the excess fatality risk for children (ie, negative effectiveness) combined with the lower occupancy rate on the front passenger side resulted in a smaller number of incremental QALYs saved.

Of special interest is the benefit-risk ratio for front passenger air bags, where the lives of about 10 adults are being saved for each child killed using the point estimates in the reference case. As Figure 1 indicates, this ratio is uncertain and changes dramatically as a function of the assumed effectiveness for children. The ratio will need to be reevaluated in the future as vehicles with front passenger air bags are resold to owners with less income and education.

Deterministic single variable sensitivity analyses were performed in which the value of each input variable was varied by ±30% to explore the behavior of the model (Table 3). These results indicated that estimates of cost-effectiveness for various air bag strategies were substantially influenced by the unit cost of the air bag systems, the effectiveness rates for the systems, the baseline fatality rates, the ratio of injuries to fatalities, and the real discount rate. Results were less sensitive to changes in valuations of nonfatal injuries, the cost of treating MAIS 2 to 5 injuries, the maintenance and replacement costs, and the air bag deployment rate.

Considering the full ranges of the uncertain model inputs, the choice of discount rate and the effectiveness rates for the systems have the largest impacts on the model output. As shown in Table 2, applying a discount rate of 5% causes the incremental cost-effectiveness ratio to worsen from $24 000 to $37 000 for the driver's side air bag system and from $61 000 to $91 000 for the dual air bag system.

As shown in Table 3, decreasing the effectiveness of air bags in reducing mortality and morbidity in adults aged between 10 and 64 years by 30% (from 13% to 9%) increased the cost-effectiveness ratio for the driver's side air bag by 54% to $37 000 per QALY and for the front passenger air bag by 59% to $97 000 per QALY. These disproportionate increases occur because the lower effectiveness rate increases the costs (by reducing the medical savings) and decreases the number of QALYs saved. At an effectiveness rate of 17% for adults aged between 10 and 64 years, the cost-effectiveness ratio improves from $24 000 to $16 000 per QALY saved for the driver-only air bag and from $61 000 to $43 000 per QALY saved for the addition of a dual air bag system. Sensitivity of the cost-effectiveness ratios for both the effectiveness for adults aged between 10 and 64 years and the discount rate is demonstrated in Figure 2.

Efforts to increase adult safety belt use toward 100% could save lives in nonfron-

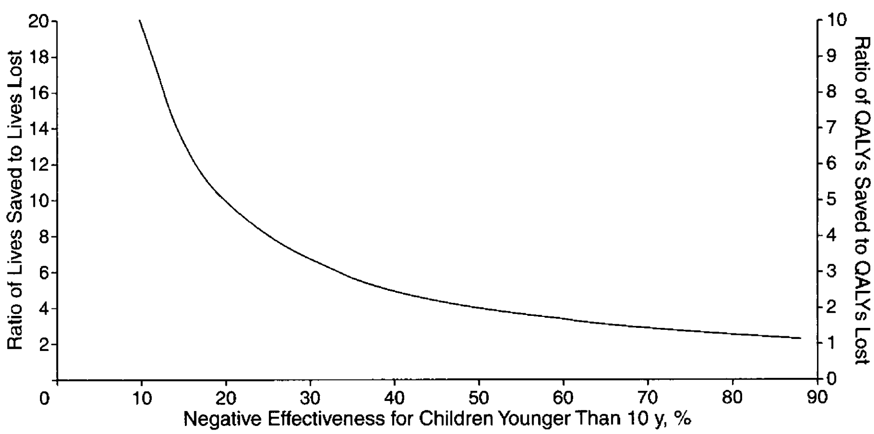

Figure 1.—Risk-benefit ratio for front passenger air bags as a function of the effectiveness for children (undiscounted). QALYs indicates quality-adjusted life-years.

Table 3.—Sensitivity Analysis Results: Changes in Cost-effectiveness Ratios (Dollars in Thousands per QALY)*

	Cost-effectiveness Ratio When Values Changed ±30%		Cost-effectiveness Ratio for Values Changed Over Plausible Range (if Different)	
Uncertain Variable Changed	Driver	Dual	Driver	Dual
Base case	24	61	...	...
Installation costs per car	33-15	79-43	28-19	67-56
Replacement costs	24-24	62-60	25-23	75-60
Maintenance costs	24-23	63-59	25-22	67-55
Cost per MAIS 2-5 and per fatality	21-26	58-64	...	...
Effectiveness for adults 10-64 y	17-37	44-97	...	...
Effectiveness for adults >64 y	23-24	60-62	...	...
Effectiveness for children <10 y	24	65-58	...	...
All effectiveness estimates	16-37	41-110	...	...
Baseline fatality rates	16-37	45-91	...	...
MAIS 2-5 injuries to fatalities ratio	18-33	49-80	...	...
QALY losses	18-34	47-87	...	...

*QALY indicates quality-adjusted life-year; MAIS, maximum Abbreviated Injury Scale; and ellipses, not applicable.

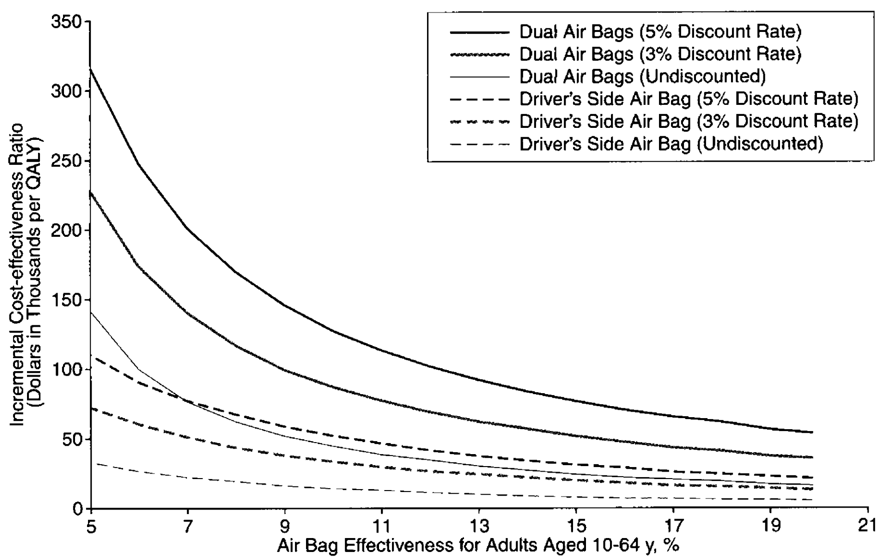

Figure 2.—Sensitivity of incremental cost-effectiveness ratios ($1000 per quality-adjusted life-year [QALY] for driver's side and front passenger air bags) as a function of air bag effectiveness for adults aged 10 to 64 years and discount rate.

tal crashes and prevent many air bag–induced injuries. However, such efforts would not necessarily improve the incremental cost-effectiveness ratios for air bags because at higher rates of use belts will prevent some of the fatalities and injuries that are now prevented by air bags. Since Ferguson[9] finds an approximately 30% lower overall effectiveness of air bags for belted occupants than for unbelted occupants, we adjusted the effectiveness estimates accordingly to 9% for belted adults aged between 10 and 64 years and to 3% for belted adults older than 65 years. Thus, if all adults wore safety belts, the cost-effectiveness ratios would change from $24 000 per QALY to $38 000 per QALY saved for the addition of a driver's side air bag to safety belts and from $61 000 per QALY to $102 000 per QALY saved for the additional front passenger air bag.

Several European countries (eg, France and Germany) used to require all children younger than a specified age (10 or 12 years) to be seated in the rear of a motor vehicle (when a rear seat exists). Despite recent amendments to their laws that now allow children to sit in the front if they are properly restrained, it is still customary for children in these countries to ride in the back seat of cars. If similar behavior existed in the United States, then safety benefits would result. In our model when children younger than 10 years are moved to the back seat (with the front seat left empty), the incremental cost-effectiveness ratio for front passenger air bags declines from $61 000 per QALY to $51 000 per QALY, since the danger of air bags to children is eliminated.

If air bags are not effective at reducing MAIS 2 to 5 injuries, then including resources and QALYs saved by avoiding injuries leads to an underestimation of the cost-effectiveness ratios. Considering only the reductions in fatalities associated with air bags, the ratios would be $105 000 per QALY and $235 000 per QALY for driver's side and front passenger air bags, respectively.

The effect of air bags on the safety of adults older than 65 years is uncertain. If air bags are actually as effective for adults older than 65 years as they are for adults between 10 and 65 years, then the ratios drop to $22 000 per QALY saved and $55 000 per QALY saved for driver's side and front passenger air bags, respectively. Alternatively, if the air bags are 0% effective for elderly adults, the ratios increase to $25 000 per QALY saved and $65 000 per QALY saved for driver's side and front passenger air bags, respectively.

If years of life saved are not adjusted for the average health-related quality of life in the population, the cost-effectiveness ratio would fall from $24 000 per QALY saved to $22 000 per QALY saved for the driver's side air bag, and from $61 000 per QALY saved to $55 000 per QALY saved for the dual air bag system. Using an alternative health state classification system as a source of community weights, such as the *Years of Healthy Life*, did not change our qualitative results ($27 000 per QALY and $69 000 per QALY for driver's side and front passenger air bags, respectively).

COMMENT

We compared the cost-effectiveness of adding driver's side air bags to safety belts with that of adding front passenger air bags to the driver-only air bag system. Our analysis revealed that the addition of a driver-only air bag costs $24 000 per QALY saved with current rates of safety belt use. The addition of a front passenger air bag, making a dual front air bag system, costs $61 000 per QALY beyond the savings with a driver-only air bag. To the best of our knowledge, this analysis represents the first cost-effectiveness evaluation of air bags using the real-world effectiveness data that are now available. These figures are applicable only to US air bag systems and do not necessarily apply to the somewhat different air bag designs now available in Australia and parts of Europe, where road conditions and safety belt usage rates are also quite different.[44] There is also some variability in the design of US airbags that may be relevant to cost-effectiveness, but that was not analyzed here.

The estimated benefit-risk ratio for front passenger air bags deserves serious consideration by decision makers. One can question whether it is appropriate to maintain a mandatory policy that causes a net increase in mortality risk to children, even though the lives of 10 adults are being saved for each child that is lost. We are aware of no other mandatory health measure in the United States with a benefit-risk ratio so close to 1.

The net safety benefits and cost-effectiveness of dual air bags would improve considerably if the United States were to adopt policies that encourage or require children to sit in the rear seat. More and proper use of child restraints would also be useful. On the other hand, efforts to increase generally the rate of adult safety belt use, although essential in their own right,[34,35] would reduce the incremental cost-effectiveness of air bags.

The true cost-effectiveness ratio for the front passenger air bag may be worse than our analysis suggests, because effectiveness information is limited. The front passenger air bag is larger, reflecting greater variability in passenger position at the time of deployment, but even this design feature may not be adequate to achieve the effectiveness rates documented for driver's side systems. In addition, US air bag systems were optimized to protect an unbelted 76.5-kg adult male, which may cause effectiveness on the front passenger's side (where a disproportionate share of women and children are located) to be lower than the effectiveness achieved on the driver's side. Further research on the effectiveness of front passenger air bags is needed.

The preference weights for health-related quality of life are subject to change as methodological developments continue. For example, the FCI data were elicited from a convenience sample that included several subgroups of the population and used rating scales whose interval properties are controversial.[45] Ongoing FCI validation efforts will improve the estimates of the proportions of injuries that lead to some persistent functional disability and might change the preference values assigned to those injuries. Since the values for adults were assumed to apply directly to children and the elderly in our analysis, research suggesting differences between subgroups could also change the results.

Since there is no consensus on which particular set of community weights for the general population should be used in studies to inform resource allocation, the quality adjustments for the years of life saved as a result of preventing fatalities could also change. We used time trade-off, community-based preference weights from the BDHOS in the reference case. If years of life saved are not adjusted for the average health-related quality of life in the population, the cost-effectiveness ratio would fall from $24 000 per QALY saved to $22 000 per QALY saved for the driver's side air bag and from $61 000 per QALY saved to $55 000 per QALY saved for the dual system. These smaller ratios for air bags should be used when comparisons are made with other lifesaving interventions that did not adjust for health-related quality of life. We found that using an alternative health state classification system (the *Years of Healthy Life*) did not change our qualitative results ($27 000 per QALY for the driver's side air bag and $69 000 per QALY for the front passenger air bag).

No consensus currently exists about what levels of expenditures are cost-effective, and consequently it is difficult to make absolute statements about whether an intervention is a worthwhile safety investment. We can compare the marginal cost-effectiveness of interventions society has chosen to accept and those that it has not. For example, screening for hypertension costs $12 200 to $42 000 per year of life saved (in 1993 US dollars)[46];

screening for carotid stenosis in asymptomatic persons costs $120 000 per QALY saved (in 1994 US dollars)[47]; and renal dialysis costs $30 000 to $35 000 per year of life saved (in 1990 US dollars).[48] In many preventive interventions, the actual cost-effectiveness ratio is dependent on the risk of the group being targeted and the intensity of the proposed intervention. For instance, the ratio for cervical cancer screening every 4 years has been reported to be $10 000 per QALY; increasing the frequency to every 3 years results in an incremental ratio of $184 500 per QALY; increasing the frequency to every 2 years results in an incremental ratio of $262 800 per QALY.[49] On the other hand, cervical cancer screening for people in the low-income elderly population who have not been screened in recent memory has been reported to be cost saving,[50] in the same way that we showed manual safety belts were cost saving (even at 50% use rates). These examples of cost-effectiveness ratios should be compared with the ratios for air bags with caution because they are not all based on the same assumptions and methods that were recently recommended by the Panel on Cost-effectiveness in Health and Medicine.[20,21,51]

Cost-effectiveness ratios for air bags are comparable to other well-accepted measures in preventive medicine. Immediate steps can be taken to enhance the cost-effectiveness of front passenger air bags, such as moving children to the rear seat and increasing the rate at which children are properly restrained in crashes.

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