

Review of Regulatory Emphasis on Transportation Safety in the United States, 2002–2009: Public versus Private Modes

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The U.S. Department of Transportation is responsible for implementing new safety improvements and regulations with the goal of ensuring limited funds are distributed to where they can have the greatest impact on safety. In this work, we conduct a study of new regulations and other reactions (such as recalls) to fatal accidents in several different modes of transportation implemented from 2002 to 2009. We find that in the safest modes of commercial aviation and bus transport, the amount of spending on new regulations is high in relation to the number of fatalities compared to the regulatory attention received by less safe modes of general aviation and private automobiles. Additionally, we study two major fatal accident investigations from commercial aviation and two major automotive recalls associated with fatal accidents. We find differences in the cost per expected fatality prevented for these reactions, with the airline accident investigations being more cost effective. Overall, we observe trends in both the automotive and aviation sectors that suggest that public transportation receives more regulatory attention than private transport. We also observe that the types of safety remedies utilized, regulation versus investigation, have varying levels of effectiveness in different transport modes. We suggest that these differences are indicative of increased public demand for safety in modes where a third party may be held responsible, even for those not participating in the transportation. These findings have important implications for the transportation industry, policymakers, and for estimating the public demand for safety in new transport modes.

KEY WORDS: Cost effectiveness; regulation; safety; transportation

1. INTRODUCTION

Travel-related fatalities continue to be a leading cause of accidental death in the United States,⁽¹⁾ despite significant improvements in recent decades.⁽²⁾ In attempting to improve safety performance, one important constraint of new safety measures is cost, for which the U.S. Department of Transportation

(DOT) uses the guideline of the value of statistical life (VSL), most recently set at \$9.1 million.⁽³⁾ Such constraints avoid undue financial burden on individual travelers and commercial transportation while ensuring that funds are not overallocated to a single issue but spread across multiple risk sources.

In this article, we conduct a survey of the cost of U.S. federal government regulations for safety enhancement in various modes of transportation, including commercial air carriers, commuter and air taxi, general aviation, private automobiles, and buses. This survey is intended to reveal how resources have been allocated for different modes of transportation. We will seek to uncover whether public demand for safety varies across different

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modes of transportation and, if so, to determine why this might happen. We also investigate four major transportation safety cases from the past decade, two from commercial aviation and two from automobiles, to attempt to determine if their remedies are cost effective. In each of these cases, we consider a system design flaw related to a miscalculation, manufacturing or maintenance error, or unexpected operating condition that led to a risk of fatal accidents. We determine the break-even point of the investment by calculating the probability of a fatality prior to the safety improvement necessary to justify the cost of the improvement. Through this demonstration, we discuss the cost effectiveness of the current safety improvement cycle in the civil transportation sector.

Several significant prior works have examined the way the cost effectiveness of safety improvements has been analyzed. Viscusi and Aldy⁽⁴⁾ provide a detailed overview of various factors affecting the applied VSL. Morrall⁽⁵⁾ and Tengs *et al.*⁽⁶⁾ both provide reviews of the cost effectiveness of previously implemented or proposed life-saving measures across many different fields. Cropper and Portney⁽⁷⁾ outline some of the difficulties faced by regulators and policymakers in attempting to quantify cost effectiveness for new safety measures. Hammitt and Graham⁽⁸⁾ outline the difficulty in assessing survey respondents' willingness to pay for safety, particularly in the case of highly unlikely events. Arrow *et al.*⁽⁹⁾ provide a discussion of the ways in which cost-benefit analysis might be utilized to inform policy decisions.

Air travel has enjoyed many advances in safety technology since its inception. Safety enhancement in aviation is achieved not only by the evolution of technology, but also by incremental design improvements triggered by accidents. There were several epoch-making accidents that facilitated the evolution of the safety system,^(10,11) such as repeated accidents of the De Havilland Comet in the 1950s leading to the recognition of metal fatigue. Aviation accidents have high public profiles due to a potential for hundreds of fatalities in a single event. However, past research on the economics of aviation safety,⁽¹²⁻¹⁵⁾ mainly triggered by the public concerns over airline deregulation in 1978 in the United States, showed that market forces do not provide sufficient incentives for additional safety improvement. Thus, one important incentive for safety enhancement for air travel is safety measures mandated by laws and government regulations.

Private automobiles have also seen a great improvement in safety over recent decades. Safety

features such as seat belts and air bags have become standard on all new vehicles, and campaigns for and in some cases laws requiring the use of seat belts have reduced the morbidity of accidents.⁽¹⁶⁾ The advent of crash testing performed by the National Highway Traffic Safety Association (NHTSA) starting in 1979 has allowed for objective measurement of safety and facilitated competition between auto manufacturers on their safety performance.⁽¹⁷⁾ A major issue for improving highway safety has been related to driver behavior, such as speeding, impaired driving, distracted driving, or the use of safety devices such as seat belts.⁽¹⁷⁾ There is substantial investment by local governments in enforcing laws that promote safe driver behavior. Enforcement of pilot training and responsible behavior is stricter in commercial air travel, where a small group of highly trained pilots receive much more oversight by the FAA, relative to the standards for private automobile drivers.

The outline of the article is as follows: first, we provide a review of relevant safety-related transportation data for the time period of 2002–2009. We then provide an overview of the cost of regulations issued for each transport mode as estimated by the U.S. Office of Management and Budget. We next review four major safety interventions, two commercial aircraft accident investigations and two private automotive recalls, in order to determine their cost effectiveness. Finally, we discuss our findings from these studies and how they may impact future transportation innovations such as driverless vehicles.

2. TRANSPORTATION SAFETY AND REGULATION

2.1. Safety Statistics

In order to examine the emphasis of the U.S. government on transportation safety, we surveyed the accident-related statistics and economic impact of new safety regulations enacted between 2002 and 2009, the final year in which we have comprehensive safety review data for all of the considered transport modes.

To understand resource allocation for transportation safety, we must first quantify the level of safety in each transport mode. We utilize the conventional metric of fatalities per billion passenger miles³ traveled. Data for passenger miles traveled and

³Passenger miles represent the total vehicle miles traveled multiplied by the average passenger load for a given mode.

fatalities for various modes of transportation for years 2002–2009 were obtained from the 2010 National Transportation Statistics report. We categorized the mode of aviation according to the Code of Federal Regulations (CFR). CFR Part 121 is the regulation governing scheduled commercial airliners (we call it “commercial air” in this article); CFR Part 135 governs on-demand air taxis and scheduled commuter carriers, such as business jets and regional airlines (“commuter and air taxi”); and CFR Part 91 governs general aviation, which includes private aircraft such as individual-owned aircraft or business jets.

Additionally, the report contains safety statistics for highway transport, from which we distinguish private automobiles (cars, sport utility vehicles [SUVs], light trucks, and motorcycles) and buses. Since the number of passengers involved in private transport is not explicitly known, we rely on survey estimations. The 2009 National Household Travel Survey⁽¹⁸⁾ offers estimates of number of passengers and average distance traveled, from which we can determine passenger miles and total departures. Similarly, the annual FAA General Aviation and Part 135 Activity Survey⁽¹⁹⁾ provides an estimation of the total number of departures for both general aviation and air taxi operations. However, there are no data regarding the average number of passengers on these trips, and therefore we assume ranges of load factors to compute passenger miles traveled for these modes.

Table I shows the number of fatalities per billion passenger miles by mode of transport. We see that air carrier would be judged to be the safest mode, and roughly 250 times safer than private automobiles. General aviation, even with our highest estimates for passenger loads, is by far the least safe mode, while commuter and air taxi safety is comparable to private automobiles. Buses rank as the second safest mode, but still are nearly an order of magnitude less safe than air carriers.

2.2. Regulation Review

Next, we consider the economic impact of federal government regulations that were enacted over the same time period. The transport safety regulation system in the United States is complex. A review we have conducted on <http://www.regulations.gov> yielded over 3,500 relevant regulations published from 2000 to 2009 by the Federal Aviation Administration (FAA), Federal Motor Carrier Safety Administration (FMCSA), NHTSA, and the DOT.

The reason for including safety regulations that predate the numbers for transport safety indicators we report above is to include any regulations whose effects might be delayed several years.

A summary review of the number and cost of regulations reviewed by agency is provided in Table II. While there are too many regulations to list each individually, the highest cost regulations issued by each agency are explained in more detail in the following section with more listed in the Appendix. If regulations are deemed to involve a significant cost,⁴ the Office of Management and Budget (OMB) requires a cost-benefit analysis, and we use this analysis to determine the cost of each regulation to the U.S. economy and transportation industry.

2.3. Notable Regulations Reviewed

While NHTSA is responsible for the most significant cost with a total of \$73B, the FAA issued the highest number of regulations with 3,297, 2,140 of which were airworthiness directives (ADs). Only 330 of the 3,578 regulations reviewed were deemed to have a significant cost and therefore reviewed for cost effectiveness by the OMB. While regulations not deemed significant may have some nonzero cost, we feel this may be neglected due to the low cost of some significant regulations, as low as hundreds of dollars over 10 years. We additionally note that a small number of these regulations constitute a majority of the costs, so it is therefore worthwhile to consider some of these individually.

The single most expensive regulatory action of this time period is NHTSA’s Corporate Average Fuel Economy standards that cost an estimated \$47B; as this regulation has a minimal effect on transportation safety, we remove this regulation from our analysis and this cost is not included in Table II or subsequent analyses. Other significant regulations include: two regulations for \$14B and \$10B from NHTSA to improve rollover and roof crush risks, \$12B from NHTSA for the Transportation Recall Enhancement, Accountability, and Documentation (TREAD) Act (discussed in more detail in Section 2.2.3), \$13B from the FMCSA to

⁴A regulatory action is considered “economically significant” under Executive Order 12866 § 3(f)(1) if it is likely to result in a rule that may have “an annual effect on the economy of \$100 million or more or adversely affect in a material way the economy, a sector of the economy, productivity, competition, jobs, the environment, public health or safety, or state, local, or tribal governments or communities.”

Table I. Annual Fatalities per Billion Passenger Miles (Years 2002–2009)

Air Carrier	Commuter and Air Taxi	General Aviation	Private Auto	Bus
0.038 (21)	4–11 ^a (42)	30–160 ^a (560)	9.09 (41,000)	0.26 (45)

Note: The number in parentheses is the average number of fatalities per year during the period.

^aPassenger loads for commuter and general aviation are estimated at 10–25 and 1–5 passengers, respectively

Table II. Breakdown of Reviewed Federal Government Regulations by Cost and Agency (Years 2002–2009)

	FAA	FMCSA	NHTSA	DOT	Total
Number of Regulations	3,297	34	187	60	3,578
Number of Regulations with Significant Cost ^a	282	13	31	4	330
Total Significant Regulation Cost	\$7.5B	\$18B	\$73B	\$375M	\$99B
Cost of Top 3 Regulations	\$1.3B, \$1.1B, \$1.0B	\$13B, \$0.48B, \$0.38B	\$14B, \$12B, \$10B	\$280M, \$89M, \$5M	\$14B, \$13B, \$12B

^aBased on regulations with cost estimates reviewed by U.S. OMB.

update commercial driver rest requirements, and FAA regulations of \$1.3B, \$1.1B, and \$1.0B that related to maintenance on late-life aircraft, aircraft material flammability standards, and catastrophic fuel tank explosions, respectively. Regulations that are not considered significant are often FAA ADs that redesignate airspace, or any agency's updated testing requirements that do not require significant changes to existing practice; we therefore consider potential costs of such regulations as negligible.

2.4. Regulatory Attention by Transport Mode

We aggregate the above safety regulations by mode based on the description provided in the regulation documentation, calculate the dollars spent on each mode over the entire period, and compare this to the number of observed fatalities, as shown in Table III. Note that some regulations may be counted multiple times in this table if they are estimated to affect multiple transport modes. It can be seen that air carriers and buses receive much more regulatory attention per fatality than other modes. The regulation cost per fatality of air carriers is about 200 times as large as that of private automobiles.

While some of the regulations considered may have direct economic value beyond improving safety, we consider that improving safety is the primary benefit of each regulation. Based on our review of the most cost-significant regulations as shown in the Appendix, we feel this is a reasonable assumption. We must recognize that a regulation would be

deemed cost effective by the number of fatalities prevented, which we have no way of estimating. Instead, we consider the regulation cost per fatality observed, which gives us an idea of the total fatalities that could have been prevented, assuming that the number of fatalities would not have increased significantly absent the regulations. For comparison, we may consider the DOT-specified VSL, which is currently set at \$9.1 million per fatality prevented.

Using this cost per observed fatality as a metric, we find that the cost of regulations for public modes of transportation, air carriers and buses, is much higher than their private counterparts, general aviation and private automobiles. As the rate of regulatory spending per fatality in these two modes is higher than the VSL, it may be argued that regulators are responding to a higher public demand for transportation safety in these modes. Commuter and air taxis receive moderate regulatory attention as compared to commercial aviation and general aviation, while general aviation and private automobiles, the two least safe modes, received the least regulatory spending per fatality by the U.S. federal government.

3. COST-EFFECTIVENESS STUDY OF SPECIFIC FATAL ACCIDENT RESPONSES

The cost of regulations cited in the previous section is based on government estimates justifying the regulations. It is instructive to also look at the actual costs incurred to correct some well-publicized safety defects. Such an examination reveals that there are

Table III. Total Federal Regulation Cost per Fatality in Millions for Various Transport Modes (Year 2002–2009)

Air Carrier	Commuter and Air Taxi	General Aviation	Private Auto	Bus
\$31 (\$6.4)	\$11 (\$4.8)	\$0.50 (\$2.8)	\$0.15 (\$63)	\$69 (\$31)

Note: The number in parentheses is the total cost in billions during the period.

additional costs, including the cost of investigations to determine what safety defect caused fatalities, and the cost to recall vehicles. In this section, we propose a method of calculating the cost effectiveness of these investigations and demonstrate its application on example case studies from transportation and aviation. These few cases are not intended as representative of the current state of transportation policy and are simply provided as examples of how the proposed cost-effectiveness calculation might be applied.

3.1. Cost-Effectiveness Measures of Safety Investigations and the Resulting Remedies

Accident investigations have been playing a central role in improving aviation safety. Elaborate investigations identify the probable causes of accidents and lead to safety recommendations to prevent similar accidents from occurring in the future. Independence of investigators from other authorities and separation from blame guarantees the quality of investigations.^(20,21) More recently, it has been proposed that the approaches and methods of aviation accident investigation be extended to a wider context of social concerns, such as natural disaster or economic fraud.^(22,23) Aviation is also a mode of civil transportation for which accident investigation is mandated in the United States, and the National Transportation Safety Board (NTSB) is responsible for it.

Similarly, the NTSB carries out accident investigations for private automobiles, though due to the sheer number of accidents, not all will receive NTSB attention. When a safety issue is found requiring attention, typically after one or more accidents take place, the DOT may mandate a recall of a certain vehicle or family of vehicles. As with aviation accidents, a series of accident and safety investigations may be undertaken; however, unlike some aviation cases, this is a relatively negligible cost for automobile recalls. It then falls to the responsibility of the manufacturer to provide an appropriate safety remedy for the affected vehicles and to cover the costs of this repair. Though automotive recalls and aircraft

accident investigations are not identical, we view the results of both actions in terms of reacting to a safety issue with new measures as similar enough for comparison.

For a cost-effectiveness study, we deploy a simple break-even calculation of the investment in an accident investigation or recall and focus on fatal accidents. The expense, C_{inv} , is the cost of the investigation and the following safety remedies, if needed. The payoff is the expected monetary value of lives to be saved, V_{saved} , in the future as a result of the investigation and remedies. Potential future fatalities related to an accident are calculated by the product of the expected number of fatalities N_f that would result from a similar accident, the number of airplanes or automobiles N_a that have the same failure potential, and the probability of reoccurrence of the accident in the remaining lifetime. For estimating N_a , one may take into account not only existing vehicles but also not-yet-built ones that will potentially benefit in the future from the improved design and safety regulations. Accident investigation has the potential to change the probability of accident reoccurrence, through implementation of the recommended safety measures. On this basis, the expected monetary value of lives to be saved (V_{saved}) can be calculated as

$$V_{saved} = V_{life} N_f N_a (P_{before} - P_{after}), \quad (1)$$

where V_{life} is the value of a single life, P_{before} is the probability of a fatal accident occurring per remaining lifetime of one vehicle before safety improvement is applied, and P_{after} is the probability of an accident after the improvement is applied. The break-even point happens when the invested cost in the investigation and remedies, C_{inv} , is equal to V_{saved} .

The dollar value of a fatality, V_{life} , is defined as the amount we are willing to give up in exchange for a small decrease in the probability of one less fatality, called the value of a statistical life.⁽²⁴⁾ This is a common approach in economics, used to evaluate effectiveness of policies in medicine, the environment, and other areas. How much a society should invest in preventing fatalities is controversial, as seen in many ongoing discussions in different communities, e.g.,

healthcare, transportation, the environment, etc. Viscusi⁽²⁵⁾ analyzed data on worker deaths across different industries, and suggested that the value of a life lies in the range of \$4.7–\$8.7 million. In aviation, economic values used in investment and regulatory decisions of the DOT were analyzed and determined. The guidance led to the value of \$6.2 million per fatality adopted in 2011⁽²⁶⁾ and most recently updated it to \$9.1 million in 2013.⁽³⁾ Similarly, in Europe, an aviation fatality avoided is valued at €4.05 million by the European Transport Safety Council in 2003.⁽²⁷⁾

For a given investigation and remedy cost C_{inv} , it is possible to calculate how much we spend to prevent the loss of one life in the future as:

$$C_{1life} = \frac{C_{inv}}{N_f N_a (P_{before} - P_{after})}. \quad (2)$$

This measure would be compared to the DOT guideline to determine whether accident investigation is cost effective or not. On the other hand, the value of lives to be saved can be used as the cost-effective threshold of the invested cost $C_{inv,th}$ or the accident probability $P_{before,th}$, assuming that P_{after} is zero as in Equations (3) and (4), respectively,

$$C_{inv,th} = V_{1life} N_f N_a P_{before}, \quad (3)$$

$$P_{before,th} = \frac{C_{inv}}{V_{1life} N_f N_a}. \quad (4)$$

Note that these equations are not intended to provide a precise estimate of cost effectiveness of investigations as many of the terms in these equations are not known and can never be measured. However, we may be able to estimate these terms in order to produce a Fermi estimate of the probability of an accident before an intervention as well as the break-even probability that would justify the cost of the reaction. When these numbers are comparable, we are unable to say whether an intervention was truly effective; instead, we use this analysis as a way to discuss differences in cost effectiveness between various reactions to accidents.

3.2. Case Studies for Investigations into Fatal Accidents

We select four cases of responses to fatal accidents from roughly the same time period as our study of transportation regulations. These four cases should not be regarded as a complete list of all actions taken to respond to transportation safety risks during this time period. They are selected as, in

the opinion of the authors, they represent the most noteworthy safety investigations during this period for commercial airlines and private automobiles, respectively. Because of their high profile, we are also able to obtain much of the data needed for our analysis. By studying specific cases of reactions to safety issues, we hope to better understand the situations in which a proposed remedy is likely to be cost effective. This is not intended to represent the broad state of transportation safety or policy; these case studies simply are used to demonstrate the application of the cost-effectiveness calculation introduced in the previous section. Recognizing that the analysis performed is speculative due to limited available information, we take conservative assumptions regarding costs and probabilities of accidents recurring in order to consider any potential cases as much possible.

3.2.1. American Airlines Flight 587

The first example is the fatal accident of American Airlines Flight 587, which occurred on November 12, 2001. The airplane, an Airbus A300-605R, crashed into a neighborhood in Belle Harbor, New York, after taking off from the John F. Kennedy International Airport. All 260 people aboard and five people on the ground were killed.^(28,29)

NTSB determined that the probable cause was “the in-flight separation of the vertical stabilizer as a result of the loads beyond ultimate strength that were created by the first officer’s unnecessary and excessive rudder pedal inputs (when the pilot reacted to wake turbulence).” The NTSB report concluded that “[t]he American Airlines Advanced Aircraft Maneuvering Program excessive bank angle simulator exercise could have caused the first officer to have an unrealistic and exaggerated view of the effects of wake turbulence.” The report also discussed a widespread misunderstanding among pilots about performance of the rudder limiter system; pilots believed that a limiter would prevent structural damage no matter how they moved the control. However, the limiter did not take into account structural damage caused by repetitive opposite direction rudder inputs that resulted in the excessive load.

FAA issued an AD in 2011⁽³⁰⁾ requiring a modification to the rudder control system, called the pedal travel limiter unit (PTLU). The AD estimates the implementation cost of PTLU for 215 airplanes in the fleet at \$42,677,500. For the cost-effectiveness study, the number of potential fatalities was estimated at 213, based on the typical passenger

capacity of the model (266 passengers) and a load factor of about 80%, and nine crewmembers. Adding the costs of accident investigation and other safety remedies (e.g., pilot training), which are not publicly available, the total invested cost is roughly estimated as \$52 million U.S. 2013 dollars.

Using above data, we calculate the cost-effectiveness threshold of the accident probability $P_{\text{before,th}}$ defined in Equation (4). Based on \$9.1 million for V_{life} , $P_{\text{before,th}}$ is estimated at 1.2×10^{-4} in the remaining lifetime of a single airplane. This probability corresponds to 6.0×10^{-9} per flight, assuming that the remaining life time is roughly half the design service goal of 40,000 flight cycles for the airplane.⁽³¹⁾ This rough estimate is based on the analysis of the available operating data of A300 class aircraft in the TranStats database.⁽³²⁾ It is remarkable that this probability is substantially smaller than the actual total rate of fatal accidents per departure from 2002 to 2009, 1.8×10^{-7} . Therefore, it can be said that this accident investigation is cost effective unless the probability of the accident is extremely small.

3.2.2. Alaska Airlines Flight 261

The next example is the crash of Alaska Airlines Flight 261, which occurred on January 31, 2000. Fatalities included two pilots, three cabin crewmembers, and 83 passengers. The airplane, MD-83, was destroyed by impact forces.⁽³³⁾ The NTSB concluded that the probable cause was “a loss of airplane pitch control resulting from the in-flight failure of the horizontal stabilizer trim system jackscrew assembly’s acme nut threads. The thread failure was caused by excessive wear resulting from Alaska Airlines’ insufficient lubrication of the jackscrew assembly.”

According to the NTSB report, several factors contributed to the accident. First, lubrication of the nut threads was not adequately performed. Second, there were inappropriately wide lubrication and inspection intervals for the wear condition; because of this, wear exceeding its critical condition could not be discovered before the following lubrication or inspection point. The FAA issued ADs⁽³⁴⁻³⁹⁾ requiring repetitive inspections and lubrication. These improvements were applicable not only to MD series but also to Boeing airplanes. Table IV shows the fleet sizes of airplane models to which the ADs were applied, and the passenger sizes of those airplanes obtained from the company’s website. We roughly assume that five inspections and lubrications would

Table IV. Parameters Estimated for Alaska Airlines Case

	Fleet Size ^a	Passenger Size (model)
MD-80	1,218	155 (MD-83)
Boeing-767	411	218 (767-300ER)
Boeing-737	1,641	162 (737-800)
Boeing-747	236	416 (747-400)
Boeing-757	730	280 (757-300)
Boeing-777	203	365 (777-300ER)

^aFleet size registered in the United States.

be needed in the rest of the lifecycle of each airplane, and the overhaul of nut and screw, which was applied only to Boeing-737, is a one-time item. Based on the work hours and labor rates provided by the ADs, as well as the estimated cost of inspection, we calculate the total cost for the safety improvements as roughly \$18.5 million U.S. 2013 dollars.

In the same manner as the previous example, we calculate the cost-effective threshold of the accident probability as 2.5×10^{-6} per lifetime of a single airplane. Here, we used \$9.1 million for V_{life} , and the number of potential fatalities to be saved is calculated by summing up $N_f N_a$ of each airplane model shown in Table IV with a load factor of 80%. This probability can be converted into 1.2×10^{-10} per flight, which is also much lower than the actual fatal accident rate (1.8×10^{-7}). As with the previous example, we assume, based on the analysis of the TranStats database for Boeing aircraft, that the remaining life of the airplane is 20,000, half the design service goal of a typical airplane.

Despite being the two most fatal aviation accidents in the United States over the time period we cover in this study, their total safety regulation cost (about \$67 million) only represents about 1% of the total regulation cost of \$7.5B as described in Table II.

3.2.3. Ford/Firestone Tread Separation and Rollover Recall, 2000

The first automotive recall considered is the Ford/Firestone tire recall in 2000. NHTSA found that Firestone Wilderness AT and ATX tires produced at the Firestone plant in Decatur, IL, were subject to tread separation during operation in certain conditions, particularly low pressure, high speed, and hot weather operations, which could lead to increased risk of vehicle rollover when the tires fail. In particular, these tires were installed on Ford SUVs, where it was thought that this issue would lead to a higher

risk of rollover.⁽⁴⁰⁾ Firestone issued a recall of a total of 6.5 million tires, affecting roughly 1.3 million vehicles.⁽⁴¹⁾ Though estimates vary, somewhere between 150 and 300 fatalities are thought to have been caused by this tread separation issue.⁽⁴²⁾ The total direct cost of this recall, shared between Firestone and Ford, is estimated at between approximately \$1.3 and 1.7B in 2013 dollars;⁽⁴³⁾ the cost of investigation is assumed to be negligible as NHTSA's entire annual highway safety program budget is roughly \$120M.

Using \$9.1M as the VSL, and considering an average passenger load for private automobiles as 1.5 based on the 2009 National Household Travel Survey,⁽¹⁸⁾ we calculate a threshold probability of a fatal accident per vehicle between 7.4×10^{-5} and 9.7×10^{-5} . In the case of automobile accidents, we can also estimate the actual probability of failure before the recall since we have over 1 million vehicles and hundreds of accidents. Based on the 1.3M vehicles affected and NHTSA's most likely estimate of tread-separation-related fatalities of 197,⁽⁴¹⁾ we find the probability of a fatal accident as 1.5×10^{-4} , with 5% and 95% confidence bounds of 1.3×10^{-4} and 1.7×10^{-4} . We may additionally correct this probability to account for the fact that the 6.5M tires recalled were not all at end of life, and some may have failed later had they not been recalled. However, since this would depend on individual operating conditions, driving habits, tire age, and probability of tire failure over tire life, it is difficult to make any meaningful assessment, though we conservatively estimate a range from a factor of 1.5–3 increase in fatal accident probability based on the average age of vehicles included in the recall, meaning the average wear on recalled tires between one-third and two-thirds of the expected tire life of roughly five years or 60,000 miles.

We find that the estimated range of probability of a fatal accident is only slightly higher than the range of threshold probability of failure based on the data collected. This indicates that the safety increase due to the recall likely at least broke even with the costs, and could be as much as a factor of 3 more. However, we note that this is a much narrower margin than seen with the previous two cases of accident investigations in air travel.

It should be noted that this investigation led to one of the most cost-significant regulations for private automobiles during the time of our survey. This is the TREAD Act, which cost a total of \$24B, 38% of all private automotive regulation costs during our survey period from 2002 to 2009. However, this regulation deals exclusively with the way manufacturers

report recalls and safety concerns to NHTSA, and does not specifically address the issue of tread separation or rollover, and therefore this cost is not included in our calculations for this investigation.

3.2.4. *Toyota Unintended Acceleration Recalls, 2009/2010*

The second auto case considered is actually two related recalls that occurred at roughly the same time that dealt with the unintended acceleration accidents involving Toyota vehicles in 2009 and 2010. The first recall replaced floor mats in some Toyota vehicles that were believed to potentially cause the accelerator pedal to stick. The second dealt with wear in the accelerator pedal that could cause sticking unrelated to the floor mats. These recalls affected 2.23M and 4.44M vehicles, respectively. Due to overlap in the recalls, a total of nearly 5M vehicles were recalled. Toyota vehicles with fatal accidents attributed to unintended acceleration account for as many as 48 deaths,⁽⁴⁴⁾ though DOT investigations concluded that many such accidents may actually be related to driver error.⁽⁴⁵⁾ The direct cost of the recalls, as reported by Toyota, was \$1.12B⁽⁴⁶⁾ and the cost of the investigation is again assumed to be negligible in comparison.

Again, using the VSL of \$9.1M and an average passenger load of 1.5, we find that the threshold probability of a fatal accident per vehicle for cost effectiveness is 1.65×10^{-5} . We again estimate the actual probability of failure based on the number of fatal accidents observed, and find a nominal value of 4.96×10^{-6} with confidence bounds of 3.00×10^{-6} and 6.91×10^{-6} . As with our previous auto recall example, we recognize that these estimates are based on some vehicles that are not at end of life. However, in this case, we consider that it may be reasonable to assume that the probability of this specific accident is constant over the lifetime of the vehicle, and we may try to estimate the average age of vehicles in the recall. Based on available data, we consider that the average vehicle recalled was five years old, with a useful life of 15 years. Since we assume that the probability of an accident is constant over time, we may simply correct our calculated probability of failure by a factor of 3, such that we find the estimated probability before the recall as 1.49×10^{-5} with confidence bounds of 9.00×10^{-6} – 2.07×10^{-5} . Even with this correction, we see that it is very likely that the probability of a fatal accident prior to the recall was below the cost-effectiveness threshold.

Since this recall happened outside the date range of our regulation study, we have no direct information about any regulations resulting from this recall and investigation. However, the authors are unaware of any current or proposed regulations related to these Toyota recalls.

4. DISCUSSION OF COST EFFECTIVENESS

Based on the studies presented in Sections 2 and 3, we may draw some conclusions about the cost effectiveness of safety measures for various modes and the allocation of resources within the U.S. transportation sector. We may also attempt to understand some broader implications for safety measures based on differences between different transport modes. However, we recognize that this discussion does not represent a complete list of factors influencing allocation of resources for transportation safety and that our review of accident investigations is limited to a small sample size due to lack of available information. The discussion in this section is not intended to propose optimal policy, but simply to summarize potential effects evident in what data we do have.

First, we find that commercial aviation receives much more regulatory attention per fatality than general aviation. At the levels of regulatory spending seen during the years considered (2002–2009), commercial aviation received regulatory spending per fatality at a rate of roughly three times the DOT VSL. At the same time, general aviation received the second lowest regulatory attention per fatality despite being the least safe mode in our study based on fatalities per passenger mile. General aviation additionally received the lowest regulatory emphasis in terms of absolute dollars spent over the time period considered at \$2.82 billion as compared to \$6.43 billion for commercial aviation. A recent study of general aviation safety by Thomas Frank at *USA Today*⁽⁴⁷⁾ found that 86% of general aviation accidents are attributed to pilot error, including cases where subsequent investigations reveal defective parts contributed to an accident. These findings suggest that public demand for safety is lower when an individual is perceived to be responsible for his or her own safety, even though this may not always truly be the case.

We consider several reasons why this disparity between modes might exist. First, while fatal commercial airline accidents may be catastrophic events involving hundreds of fatalities, general aviation accidents typically affect few people and

occur more frequently and with less national coverage. Additionally, a different level of individual responsibility exists in general aviation accidents, where those involved are at least perceived to have some control over ensuring their own safety. This personal responsibility does not exist in commercial air travel, where travelers must place their trust in the pilot to ensure their safety. These factors together may lead to a higher perceived risk from commercial air travel by the general public, which is then reflected in their demand for new regulations. Even if risks are well understood, individuals may feel that a higher level of safety is appropriate in modes where a third party is providing transportation. This concept of risk perception is one that is already well studied in existing literature. As the details of risk perception lie outside the authors' expertise, we elect not to discuss them here and instead refer readers to important works such as Slovic,⁽⁴⁸⁾ Rowe and Wright,⁽⁴⁹⁾ and Sjöberg.⁽⁵⁰⁾

This idea is reinforced by the allocation of new regulations in private automobiles and bus travel, where buses receive much more regulatory attention, possibly due to the fact that, as with the aviation case, bus accidents involve a larger number of people who are dependent on a single driver to ensure safety. Finally, in the case of private automobiles, much of the regulation and enforcement of responsible driver behavior is executed by state and local government. In that realm, we see new regulations such as requiring seat-belt use and prohibitions on using cell phones. However, the increased regulatory cost of such measures is not expected to be able to offset greatly the factor of 450 between regulatory spending per fatality between buses and private automobiles.

These findings may have implications for future developments in transportation such as partially or fully automated transport systems. Many automobile companies and research groups have made substantial efforts to develop autonomous or self-driving cars. As of 2015, four states (California, Nevada, Florida, and Michigan, as well as the District of Columbia) have legalized the use of autonomous vehicles on public roads. A 2014 University of Michigan study of public perception of autonomous cars⁽⁵¹⁾ found that 88% of survey respondents expressed concern about the prospect of riding in a fully autonomous vehicle, while over 60% also responded that the use of fully autonomous vehicles would be expected to reduce both the number and severity of accidents. These results reflect our suggestion that

entrusting one's safety to an external actor increases an individual's demand for safety. Designers of autonomous systems as well as policymakers should therefore consider the public's increased demand for safety in these new modes as they develop.

We also proposed a method for approximating the cost effectiveness of reactive safety measures like accident investigations and recalls, and reviewed two of the largest airline accident investigations and two of the largest automobile recalls from roughly the same time period as our regulation study. While both airline accident investigations were found to be easily cost effective by at least an order of magnitude based on the expected number of fatalities prevented, the automotive recalls were not so clear, with one being slightly cost effective and one likely below the cost-effectiveness threshold. This implies that these more reactive safety measures may be more likely to be cost effective for aviation compared to automobiles, though further investigation into a more comprehensive list of investigations is needed.

We propose that this observed difference might be due to two factors: the population size of the vehicles affected and the relative reliability of both systems. Though safety investigations for private automobiles are relatively inexpensive, the cost of performing a recall is often quite high even when the cost of a remedy is low due to the potentially millions of vehicles involved. Conversely, commercial aviation accident investigations may be much more costly, but the resulting safety recommendations are only implemented on several hundred aircraft or less. Compounding this issue is the relative value at risk in terms of the number of people affected per accident, which is much greater for air travel than for automobiles. This means that fixing any one issue for an airline will result in a proportionally larger increase in safety than for automobiles where a safety increase may be only marginal.

This reveals potentially important considerations for designers as well as regulators, as the types of safety issues faced in all transport modes typically have very low probabilities of occurrence, on the order of 1 in 1 million or less. This means that uncovering and preventing safety issues during the design process requires extensive testing and simulation, which is costly, and these costs are ultimately passed on to consumers. These costs are only exacerbated when the method of failure is unknown or difficult to predict, such as those related to operator error. We see that for airliners, safety concerns are easier to detect due to the rarity

of accidents and in-depth investigation into each accident, while with private automobiles, individual issues may be more difficult to find and are clearly more expensive to remedy due to the cost of recalls.

Furthermore, the financial incentives in commercial aviation and private automobiles are quite different. Airlines and aircraft designers may seek to improve safety beyond what is required in order to appear safe to their customers. The relative low cost of addressing safety concerns in commercial aviation does not provide adequate financial incentive for designers to attempt to avoid them, and public opinion after accidents generally affects airlines, with little impact on designers.⁽¹²⁻¹⁵⁾ Conversely, we have shown that automobile recalls pose a financial burden applied directly to automobile designers. Automobile designers face additional losses related to public perception of their brand as they compete on safety records.⁽⁵²⁾ This may suggest that the automobile market is more efficient at creating improved safety, while commercial aviation safety requires more regulatory involvement. This might help to justify the differences in regulatory attention between modes. Understanding these differences between each mode may assist in an effective balance between preventative design and testing versus oversight and improvements to existing products.

5. CONCLUDING REMARKS

We have shown that airlines and buses receive much more regulatory emphasis as measured by cost of regulation per observed fatality as compared to general aviation and private automobiles, respectively. This happens in spite of much better safety records of airlines and buses.

This could be due, in part, to nonregulatory safety actions in modes like private automobiles such as traffic enforcement and seat-belt requirements. It could also reflect the already high cost of recalls due to existing regulations as seen in our review of recalls. We also conducted an initial study of two major commercial aviation accident investigations and two major automobile safety recalls and demonstrated a cost-effectiveness calculation approach for each, finding that the two aircraft accident investigations strongly appeared to be cost effective, while the effectiveness of the two automobile recalls was less clear. Based on analysis of our regulation studies, we suggest that public demand for increased safety

appears to be affected in part by the level of personal responsibility for ensuring safety. Additionally, the effectiveness of various types of safety measures (regulation or investigation/recall) is shown to be affected by the relative number of affected vehicles, the number of lives at risk, and the relative safety level of the mode. Designers and policymakers should be aware of these effects as they work on improving existing transportation as well as the development of novel modes, and methods for cost-benefit analysis such as the one presented in this work can be utilized to estimate the cost effectiveness of proposed reactive measures. New forms of transportation such as

self-driving cars may not only need to be safer than traditional cars, but may have even more stringent safety requirements.

ACKNOWLEDGMENTS

This research was partly supported by the National Science Foundation (Grant CMMI-0927790 and 1131103). The authors gratefully acknowledge this support. They would also like to acknowledge the work of Brian DeKrey, William Schanen, and Eric Spencely who reviewed over 3,000 documents to determine the cost of federal regulations.

APPENDIX: SIGNIFICANT REGULATIONS BY ISSUING AGENCY

Table A1. Significant FAA Regulations

Document ID	Summary	Mode Affected ^a	Effective Date	Estimated Cost over 10 Years	Percentage of Total Agency Cost
FAA-1999-5401-0145	Amends inspection and record keeping for aircraft of greater than 14 years of use.	C,A	3/4/2005	\$1,350,000,000	18%
FAA-2000-7909-0043	The Federal Aviation Administration (FAA) is adopting upgraded flammability standards for thermal and acoustic insulation materials used in transport category airplanes.	C,A,G	8/2/2003	\$1,084,000,000	14%
FAA-2005-22997-0154	Amends FAA regulations that require operators and manufacturers of transport category airplanes to take steps that, in combination with other required actions, should greatly reduce the chances of a catastrophic fuel tank explosion.	C	9/19/2009	\$1,012,000,000	13%
FAA-2002-12261-009	This final rule permits the initiation of reduced vertical separation minimum (RVSM) flights in the airspace over the contiguous 48 states of the United States, the District of Columbia, Alaska, that portion of the Gulf of Mexico where the FAA provides air traffic services, the San Juan Flight Information Region (FIR), and the airspace between Florida and the San Juan FIR.	C,A,G	10/27/2003	\$579,466,667	8%
FAA-2007-28058-0008	Adopts a new airworthiness directive (AD) for various IAE turbofan engines. This AD requires removing certain No. 4 bearing oil system components from service at the next shop visit or by an end date determined by the engine model.	C	8/20/2008	\$450,371,650	6%
FAA-2000-8490-0010	This final rule amends the list of airspace locations where RVSM may be applied to include the New York Flight Information Region (FIR) portion of West Atlantic Route System (WATRS) airspace.	G	12/10/2001	\$262,000,000	3%

(Continued)

Table A1. (Continued)

Document ID	Summary	Mode Affected ^a	Effective Date	Estimated Cost over 10 Years	Percentage of Total Agency Cost
FAA-2005-20836-0046	Adopts a new AD for certain Boeing transport category airplanes related to the flammability of installed insulation blankets.	A	12/15/2008	\$177,700,000	2%
FAA-2004-18379	Fuel tank safety requirements related to electrical wiring, including updated inspection requirements for wiring systems.	C	12/10/2007	\$166,400,000	2%
FAA-2001-11133-2709	The FAA is creating a new rule for the manufacture, certification, operation, and maintenance of light-sport aircraft. Represents an overall update to manufacture of aircraft and certification of pilots.	G	9/1/2004	\$158,400,000	2%
FAA-2005-20245-0075	Amends cockpit voice recorder (CVR) and digital flight data recorder (DFDR) regulations affecting certain air carriers, operators, and aircraft manufacturers in order to improve the availability of CVR and DFDR information.	C,A	4/7/2008	\$153,636,364	2%
FAA-2001-11032-0007	This amendment implements two security design requirements governing transport category airplanes related to the security of commercial aircraft cockpit doors to unauthorized intrusion.	C	1/15/2002	\$131,000,000	2%
FAA-2003-15085-0075	The FAA is amending its hazardous materials (hazmat) training requirements for certain air carriers and commercial operators.	C,A	11/7/2005	\$107,500,000	1%
FAA-2005-23500	AD for International Aero Engines V2500 Turbofan Engines.	C	11/15/2007	\$99,338,400	1%
FAA-2000-7018-0120	The interim final rule established fees for FAA air traffic and related services for certain aircraft that transit U.S.-controlled airspace but neither take off from, nor land in, the United States.	C	8/20/2001	\$97,000,000	1%
FAA-2001-8724-0002	This final rule amends the existing airport security rules. It revises certain applicability provisions, definitions, and terms; reorganizes these rules into subparts containing related requirements; and incorporates some requirements already implemented in security programs.	C,A	11/14/2001	\$92,200,000	1%
FAA-2007-0411-0001	Revises an existing AD that applies to all Boeing Model 747 series airplanes. That AD currently requires that the FAA-approved maintenance inspection program be revised to include inspections that will give no less than the required damage tolerance rating for each structural significant item, and repair of cracked structure.	C	1/22/2008	\$90,090,000	1%
FAA-2002-12504-0001	This final rule requires improved flightdeck security and operational and procedure changes to prevent unauthorized access to the flightdeck on passenger-carrying aircraft and some cargo aircraft operated by foreign carriers under the provisions of part 129.	C,A	6/21/2002	\$83,200,000	1%

(Continued)

Table A1 (Continued)

Document ID	Summary	Mode Affected ^a	Effective Date	Estimated Cost over 10 Years	Percentage of Total Agency Cost
FAA-2004-18775	Brings U.S. European Airworthiness standards closer in regards to flight guidance systems.	C,A	5/11/2006	\$69,636,364	1%
FAA-2007-0412-0001	Revising an existing AD that applies to all Boeing Model 747 series airplanes related to corrosion and cracking certification.	C	1/22/2008	\$62,304,000	1%
FAA-2006-26722-0039	Adopts several standards of the International Civil Aviation Organization (ICAO) and requires manufacturers to incorporate certain security features in the design of new transport category airplanes related to unauthorized access to the cockpit of commercial category aircraft.	C	11/28/2008	\$60,500,000	1%
FAA-2001-10910-0484	The FAA is revising the applicability of certain collision avoidance system requirements for airplanes.	C	5/1/2003	\$59,000,000	1%
FAA-2004-18019-0006	The FAA is adopting a new AD for Honeywell International Inc. related to stage 1 disk inspection and service.	A	4/18/2005	\$58,151,000	1%
FAA-2004-18038	AD for Honeywell T53 turboshaft engines life limit reduction for certain engine components.	G	2/16/2006	\$58,000,000	1%
FAA-2001-10047-0232	The FAA is updating and revising the regulations governing operations of aircraft in fractional ownership programs.	G	11/17/2003	\$57,200,000	1%
FAA-2008-0517-0065	Establishes procedures to address congestion in the New York City area by assigning slots at John F. Kennedy (JFK) and Newark Liberty (Newark) International Airports in a way that allows carriers to respond to market forces to drive efficient airline behavior.	C,A	12/9/2008	\$54,000,000	1%
FAA-2007-28283-0013	Adopts a new AD for certain Boeing Model 737-600, -700, -700C, -800, and -900 series airplanes. This AD requires a one-time general visual inspection of frames between body station (BS) 360 and BS 907 to determine if certain support brackets of the air conditioning (A/C) outlet extrusions are installed; medium- and high-frequency eddy current inspections for cracking of the frames around the attachment holes of the subject brackets; and repair if necessary.	C	2/27/2009	\$46,216,954	1%
FAA-2001-8725-0003	This final rule amends the existing airplane operator security rule to include security requirement for additional types of operators related to terrorism and hazardous material threats.	C,A	11/14/2001	\$40,000,000	1%
FAA-2001-10428-0020	This action amends the flight data recorder regulations by expanding the recording specifications of certain data parameters for specified airplanes, and by adding aircraft models to the list of aircraft excepted from the 1997 regulations.	C	7/18/2003	\$38,000,000	1%
All Other Regulations				\$856,399,342	11%
Total				\$7,553,710,740	

^aAffected modes are defined as: C = Commercial, A = Air Taxi, G = General.

Table A2. Significant NHTSA Regulations

Document ID	Description	Mode Affected ^a	Effective Date	Estimated Cost over 10 Years	Percentage of Total Agency Cost
NHTSA-2009-0093-0001	As part of a comprehensive plan for reducing the risk of rollover crashes and the risk of death and serious injury in those crashes, this final rule upgrades the agency's safety standard on roof crush resistance in several ways.	P	7/13/2009	\$14,883,700,000	25%
NHTSA-2005-20586-0001	This final rule establishes a new federal motor vehicle safety standard (FMVSS) requiring installation of a tire pressure monitoring system (TPMS) capable of detecting when one or more of a vehicle's tires is significantly underinflated.	P,T,B	4/8/2005	\$13,899,600,000	23%
NHTSA-2007-27662-0001-0001	As part of a comprehensive plan for reducing the serious risk of rollover crashes and the risk of death and serious injury in those crashes, this document establishes a new federal motor vehicle safety standard (FMVSS) No. 126 to require electronic stability control (ESC) systems on passenger cars, multipurpose passenger vehicles, trucks, and buses with a gross vehicle weight rating of 4,536 Kg (10,000 pounds) or less.	P,T,B	6/5/2007	\$10,835,000,000	18%
NHTSA-2000-8572-0219-0001	In response to a mandate in the Transportation Recall Enhancement, Accountability, and Documentation (TREAD) Act of 2000, this agency is issuing a two-part final rule. The first part is contained in this document. It establishes a new Federal Motor Vehicle Safety Standard that requires the installation of tire pressure monitoring systems (TPMSs) that warn the driver when a tire is significantly underinflated. The standard applies to passenger cars, trucks, multipurpose passenger vehicles, and buses with a gross vehicle weight rating of 10,000 pounds or less, except those vehicles with dual wheels on an axle.	P,T,B	8/5/2002	\$8,966,200,000	15%
NHTSA-2007-29134-0005	This final rule incorporates a dynamic pole test into FMVSS No. 214, side impact protection. To meet the test, vehicle manufacturers will need to assure head and improved chest protection in side crashes.	P	11/13/2007	\$6,160,000,000	10%
NHTSA-2005-23439-0001	In 6/2003, NHTSA published a final rule establishing upgraded tire performance requirements for new tires for use on vehicles with a gross vehicle weight rating of 10,000 pounds or less. We are amending the performance requirements for snow tires used on light vehicles.	P	6/1/2007	\$1,199,000,000	2%

(Continued)

Table A2 (Continued)

Document ID	Description	Mode Affected ^a	Effective Date	Estimated Cost over 10 Years	Percentage of Total Agency Cost
NHTSA-2004-19807-0002	This final rule upgrades NHTSA's head restraint standard in order to reduce whiplash injuries in rear collisions. For front seats, the rule establishes a higher minimum height requirement, a requirement limiting the distance between the back of an occupant's head and the occupant's head restraint, as well as a limit on the size of gaps and openings within head restraints.	P	3/14/2005	\$985,140,000	2%
All Other Regulations Total				\$3,160,905,325	5%
				\$60,089,545,325	

^aAffected modes are defined as: P = Private Auto, T = Commercial Truck, B = Bus.

Table A3. Significant FMCSA Regulations

Document ID	Description	Mode Affected ^a	Effective Date	Estimated Cost over 10 Years	Percentage of Total Agency Cost
FMCSA-1997-2350-23305	Increased requirements for commercial vehicle driver rest and drive time limits.	T	6/27/2003	\$16,250,000,000	89%
FMCSA-2001-11061-0055	Improves requirements for safety audit of new commercial vehicle carriers.	T,B	2/17/2009	\$510,390,000	3%
FMCSA-2001-9709-0786	Updated requirements and penalties for commercial driver license holders related to noncommercial vehicle offenses or convictions.	T,B	1/29/2003	\$466,250,000	3%
FMCSA-2000-7017-0028	Subjects commercial passenger transport (9–15 passengers) to same safety requirements as motorcoaches.	B	9/11/2003	\$213,000,000	1%
FMCSA-1997-2210-0209	Updates medical certification requirements for obtaining a commercial drivers license.	T,B	1/30/2009	\$199,020,000	1%
FMCSA-1997-2199-0218	Updates training requirements for obtaining a commercial drivers license.	T,B	7/20/2004	\$146,410,000	1%
FMCSA-1997-2277-0093	Updated rules and requirements for obtaining prior safety records of prospective commercial drivers license holders.	T,B	4/29/2004	\$136,730,000	1%
FMCSA-2002-13015-0023	Allows for better enforcement of existing rules to prevent motor carriers from operating outside their prescribed authority.	T,B	9/27/2006	\$108,300,000	1%
All Other Regulations Total				\$206,738,750	1%
				\$18,236,838,750	

^aAffected modes are defined as: T = Commercial Truck, B = Bus.

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