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Passenger Aviation Security, Risk Management, and Simple Physics

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Abstract

Since the September 11, 2001 suicide hijacking attacks on the United States, preventing similar attacks from recurring has been perhaps the most important goal of aviation security. In addition to other measures, the US government has increased passenger screening requirements to unprecedented levels. This has raised a number of concerns regarding passenger safety from radiation risks associated with airport body scanners, psychological trauma associated with pat-down searches, and general cost/benefit analysis concerns regarding security measures. Screening changes, however, may not be the best way to address the safety and security issues exposed by the September 11 attacks. Here we use simple physics concepts (kinetic energy and chemical potential energy) to evaluate the relative risks from crash damage for various aircraft types. A worst-case jumbo jet crash can result in an energy release comparable to that of a small nuclear weapon, but other aircraft types are considerably less dangerous. Understanding these risks suggests that aircraft with lower fuel capacities, speeds, and weights pose substantially reduced risk over other aircraft types. Lower-risk aircraft may not warrant invasive screening as they pose less risk than other risks commonly accepted in American society, like tanker truck accidents. Allowing passengers to avoid invasive screening for lower-risk aircraft would introduce competition into passenger aviation that might lead to better overall improvements in security and general safety than passenger screening alone is capable of achieving.

INTRODUCTION

The September 11 attacks against the United States by Al Qaeda were arguably the most costly and damaging terrorist attacks in history. Approximately 3000 people were killed when four aircraft, hijacked by terrorists, crashed. Three of the planes struck targets chosen by the terrorists, the Twin Towers of New York City's World Trade Center and the Pentagon in Washington, DC. The fourth plane crashed into a field in Pennsylvania before it could reach its chosen target. Since then, preventing similar attacks has arguably become the most important goal in aviation security.

The United States has implemented a number of additional defensive measures with this goal in mind, which we will discuss in detail below. There are those who believe that the threat of suicide hijackings is past, including the authors of a recent congressional report, who are more concerned about the threat of explosive devices on aircraft because that threat has appeared more recently[1]. Regardless of what recent attacks have attempted, it is still important to be concerned about suicide hijackings for several reasons. The potential for destruction from suicide hijackings is, as we saw in the September 11 attacks and as we will quantify in the analysis below, far beyond what terrorists can hope to achieve through most other means. Suicide hijackings have proven themselves effective once; can we reasonably expect terrorist organizations to ignore their use forever?

In the decade since the September 11 attacks, air transportation security in the United States has added multiple defensive layers, starting on September 11 itself. Passengers on United Airlines Flight 93 learned of the other hijackings taking place that day and fought with their own hijackers for control of their aircraft. Although flight 93 crashed in a remote field, its passengers did succeed in preventing terrorists from using their aircraft as a weapon the way other aircraft were used that day. Passengers quickly learned about the risks of suicide hijackings and are now much more likely to resist terrorist acts on airliners. Also on that day the US government put fighter aircraft into the air and were preparing to intercept the hijacked airliners[2]. None of the fighters reached the airliners in time, partly because the military was not anticipating such an attack. Interception of hijacked flights is now an accepted necessity, and would certainly be used were another similar incident to occur, given sufficient reaction time.

The United States embarked on a number of military actions since the September 11 attacks that, though it may not be immediately obvious, help guard against future suicide hijacking attempts through deterrence. These actions include the invasions and occupations of Afghanistan and Iraq, as well as numerous other military strikes that have taken place in a variety of other countries including Yemen and Pakistan. These military strikes have resulted in the deaths of many high-ranking members of Al Qaeda, including its leader and founder, Osama bin Laden. Other Al Qaeda members are in custody and subject to indefinite detention and possible military prosecution. Although these actions may be questionable individually, collectively they demonstrate that the United States is still following a defensive strategy devised during the Cold War that was once described as Mutually Assured Destruction (MAD). When attacked by a weapon of mass destruction, even an *ad hoc* one like hijacked airliners, the United States seeks to destroy its attackers using any means necessary, at literally any cost, no matter how long it takes or how many innocent bystanders are hurt in the process. The United States' intensive military pursuit of Al Qaeda and its supporters almost certainly deters terrorists from attempting additional suicide hijackings.

Military deterrence is almost certainly effective, but extremely costly both literally and figuratively. Financially, the United States abandoned all pretense of budgetary discipline in its "war on terrorism," and its national debt has exploded. Paying off that debt will be a great burden to American taxpayers for many years to come. Many non-terrorist lives have been lost, including soldiers of the United States, Canada, the United Kingdom, and their allies. Noncombatants of numerous nations have also been killed as a result of these military actions. Few would dispute the value of additional effective and lower-cost defenses against future suicide hijacking attempts aside from military deterrence.

Passenger aircraft now require locked cockpit doors to prevent passengers from taking control of an aircraft during flight. These fortified doors by themselves have made September 11-style attacks more difficult to conduct. Airline pilots have expressed concern that this measure alone is insufficient to prevent another incident[3]. For example, the cockpit door still opens routinely for food service and crew restroom breaks, and a determined attacker might time his attack to get through the door during one of these opportunities. As a result, many pilots are now authorized to carry firearms into the cockpit.

As we can see, there are many new defensive layers in place to guard against suicide hijacking. Still, it seems appropriate to question whether these measures are sufficient collectively to stop an attack from a determined attacker. Although passenger vigilance, fortified doors, armed pilots, and the threat of military intervention and reprisal can thwart many attacks, is it prudent to assume that the combination of these measures will never fail? Perhaps not, considering each of these defenses can be defeated individually. There is certainly a need for additional measures, provided they are safe, effective, and acceptable to society in general.

The US Transportation Security Administration (TSA) adopted rules in late 2010 forcing all airline passengers to go through a pat-down search or a whole body imaging (WBI) scanner before boarding a flight. The pat-down search is notably intrusive, and includes a pat-down of breasts and genitals for passengers of either gender. Pat-downs have often been compared to sexual molestation. Because the physical act of a pat-down is identical to an act of sexual molestation were it to take place in another context, especially when practiced on children, it is understandable that so many passengers object to this method of screening. Anecdotal evidence suggests that the threat of pat-down searches is being used to force passengers to use WBI instead.

WBI, which involves looking through passengers' clothes using either millimeter-wave or x-ray radiation, has raised many other objections. Privacy is one concern, as the WBI process is capable of producing a naked image of a scanned passenger. Although these images are not supposed to be transmitted, the machines that take them are frequently capable of storing and transmitting the images they create. There are also many health concerns about WBI, especially for the machines that use X-rays for imaging. Efficacy is perhaps the greatest concern, even for TSA, who randomly selects scanned passengers for an additional pat-down search. WBI has a high rate of failure, including both false positives and false negatives. Perspiration can cause millimeter-wave scanners to falsely report a hidden item in a traveler's armpits, for example. Also, a cleverly-hidden item might avoid detection, as was described by Kaufman and Carlson[4].

Unlike the other defenses against suicide hijackings mentioned above, the TSA's increased security is having a noticeable negative effect on travel. The U.S. Travel Association, an industry trade group, estimated that screening requirements were causing prospective fliers to skip two to three flights per year on average. According to their research, this amounts to \$84.6 billion in lost revenue for travel-related industries, and 888,000 lost jobs[5]. The new security measures also have high direct costs, and at the time of this writing, only about a third of those costs are being passed on to travelers directly through per-ticket fees. The rest of the cost of security is being paid by taxpayers, not all of whom fly.

Increased TSA scrutiny of travelers is expanding outside the airports as well. Through its VIPR program (Visible Intermodal Prevention and Response), TSA is now screening passengers of forms of transportation not previously involved in US terrorist incidents, including bus, ferry, and rail transportation. VIPR has raised many concerns, including whether or not TSA intervention outside aviation is legal, warranted, or even effective at its stated goal of preventing terrorism.

To summarize, aviation security now focuses heavily on invasive passenger screening. Its effectiveness is questionable. It deters people from traveling. It is costly to travelers, government, and the travel industry. Perhaps it is appropriate to re-examine why such security might be considered necessary. Simple physics can help us quantify and better understand the risks of September 11-style attacks. Understanding these risks can also help us better address them in ways that also improve overall aviation safety. Accidents do happen, and the results of an accident can be just as catastrophic as a deliberate attack. Security improvements that also mitigate accident damage are obviously highly desirable.

REVIEW OF INCIDENTS INVOLVING AIRCRAFT STRIKING BUILDINGS

Most of the casualties of the September 11 attacks were occupants of the Twin Towers, skyscrapers which eventually collapsed after being struck by the two hijacked Boeing 767s. Such attacks had never been seen before, although there had been similar accidents. There was, for example, a 1945 incident where a military B-25 bomber transporting passengers struck another well-known New York City skyscraper, the Empire State Building. The building survived and the loss of life and property was considerably smaller (14 dead) than that seen in the September 11 attacks. The Empire State Building reopened to the public the week following the incident. There have been other similar incidents that followed the same pattern as the Empire State Building crash; they involved relatively few casualties and damage was minimal when compared with the September 11 attacks.

It is useful to compare these two incidents because they had notably different outcomes. The 767s used to attack the Twin Towers were much heavier and faster aircraft than the B-25 that struck the Empire State Building, so they did more damage on impact. They also carried much more fuel, which dispersed inside the structures and ignited in the crash, causing further damage that ultimately helped bring down the buildings. The Empire State Building, in contrast, remains standing to this day. Clearly aircraft design parameters dictate to a large degree the maximum damage attainable in a September 11-style attack. At first glance, it seems that planes that are lighter, slower, and carry less fuel cause less damage in an accident or terrorist attack.

By analyzing the differences between the aircraft types involved in these incidents and applying an understanding of basic physics, we can evaluate the potential for damage in the event of another September 11-style attack, or even a simple accident like the Empire State Building crash. Simple physical models involving kinetic energy and chemical potential energy can help us compare different scenarios with more familiar ones involving the controlled use of explosive materials like TNT.

KINETIC AND CHEMICAL POTENTIAL ENERGY

It is not difficult for someone with an elementary education in physics (for example, someone who has taken an introductory physics course in an American high school) to understand the potential for damage an airplane crash can have. All one needs to understand are two simple concepts: kinetic energy and chemical potential energy.

An object that is in motion has a certain amount of energy associated with that motion. This energy, known as kinetic energy, is a measure of how hard it was to get that object moving at its given speed. It is also a measure of how much damage can be done by stopping an object suddenly. To bring the object back to rest, you must transfer its kinetic energy to other forms of energy such as heat, light, sound waves, broken physical bonds in materials, air movements, and so on. A crashing airplane is no different. Once all the parts of the wreckage are at rest, the crash will have created a lot of sound, heat, light, vibrations in the earth, broken building structure, and other kinds of effects we would simply call damage from the crash. The kinetic energy will all be transformed into damage of some sort or another. The more kinetic energy there is at the start of the crash, the more damage there will be at the end.

This damage will strongly resemble the damage of the detonation of a bomb or other explosive device, which is caused when the chemical potential energy stored inside the explosive part of the device, say a quantity of TNT, is suddenly released into its surroundings.

This energy will be absorbed by its surroundings in much the same way as energy from an airplane crash is absorbed. Sound, light, heat, vibrations, structural damage, and other damaging effects will be produced as a result of that energy release.

Explosives are often categorized by their yield, which is a measure of the amount of energy the device releases upon detonation. This yield could be measured in terms of a common energy unit like a Joule, the standard metric unit for energy, but is more frequently measured in terms of the weight of TNT that could produce an equivalent explosion. This TNT equivalence is commonly used and is important because explosive devices can use many kinds of explosive materials. Nuclear weapons are perhaps the best example of TNT equivalence. They frequently have yields measured in thousands or millions of tons of TNT (i.e. kilotons or megatons), even though their explosion is primarily produced by nuclear fission or fusion instead of a pure TNT explosion. The amount of explosive material in a nuclear weapon is often orders of magnitude lower in weight than the TNT equivalent yield.

We can calculate kinetic energy K of a crashing airplane using the well-known formula

$$K = \frac{1}{2}mv^2 \tag{1}$$

where m is the mass (or, equivalently, weight) of the aircraft and v its speed. If we measure these quantities in metric units, kilograms for the mass and meters per second for the speed, our energy will be measured in Joules. There is a simple conversion factor between Joules and TNT equivalence: one metric ton of TNT releases about 4.184 billion Joules of energy according to the standard approximation used by scientists and engineers. (For reference, a metric ton weighs approximately 10% more than a US ton.)

We can thus categorize the destructive power of airplane crashes, at least in part, by the kinetic energy that they give up on impact in units of TNT equivalent in metric tons. For comparison, military air strikes using conventional, non-nuclear explosives commonly deliver total munitions loads measurable in tons. By measuring passenger aircraft kinetic energy in the same terms, it gives us a feel for how much military strike capability an aircraft can have during an accident or a September 11-style attack.

Similarly, the fuel on board a crashing aircraft contains a certain amount of chemical potential energy. This energy is released when the fuel is ignited after being mixed appropriately with oxygen found in the air. The total chemical potential energy (CPE) of an aircraft's fuel load can be calculated using the equation

$$CPE = \rho V \tag{2}$$

where V is the total volume of fuel (in liters) and ρ is the energy density of jet fuel, approximately 43.05 million Joules per liter. Alternately, this can be expressed in TNT equivalent tons using the same conversion factor used for kinetic energy. (For aircraft specifying the maximum weight of fuel instead of volume, the approximation of 1.2 liters per kilogram for jet fuel can be used to convert kilograms of fuel to liters.)

Unlike kinetic energy, which is released over a relatively short time period, much of the chemical potential energy in fuel can remain unreleased after the initial impact, depending on how much fuel burns or explodes immediately after a crash. Instead of combusting immediately, liquid fuel can be released from an aircraft's storage tanks and scatter, like other parts of the aircraft. This liquid can ignite under the right circumstances, at temperatures as low as 410°F (or 210°C), so a small fire created during the initial impact can spread to be much greater later on. It is also possible that much of the fuel will not ignite at all. For example, firefighters might act quickly and suppress any existing fires, depriving the remaining fuel of a source of ignition. Still, by measuring the total amount of chemical potential energy contained in the fuel, we can understand how much damage can be done over time by the fuel in a worst-case scenario.

ANALYSIS

In this section we will analyze specific vehicle types to determine plausible amounts of kinetic and chemical potential energy available to cause damage in crash scenarios similar to the ones mentioned above. We will first discuss the types of vehicles that are to be analyzed, and why they have been chosen. Some of the choices are more obvious than others. Next, we will compute plausible kinetic energy values for some reasonable scenarios. Chemical potential energy values will then be calculated and discussed.

Here we will consider data for the vehicle types listed in Table I. The aircraft types primarily represent a broad cross-section of aircraft used for passenger transport in the United States at the time of this writing. Table I also includes two aircraft of historical interest, as well as one ground transportation vehicle. The latter allows us to compare

TABLE I. Vehicle types for analysis.

Vehicle Type	Maximum Passenger Capacity
Airbus A320-200	180
Airbus A380-800	853
Boeing 737-700	148
Boeing 747-400ER	524
Boeing 757-200	234
Boeing 767-200	290
Bombardier CRJ700	78
Bombardier Q400	80
Lockheed L-188 Electra	98
North American B-25 (bomber)	6
Gasoline delivery tanker truck	2

aircraft disasters with something most of us are a bit more familiar with: tanker truck accidents.

The Boeing 757-200 and 767-200 were essentially the aircraft types used in the September 11 attacks. Two 767s struck the World Trade Center and brought down the Twin Towers. One 757 struck the Pentagon, killing 184 people aboard the aircraft and in the building. The other 757 crashed into a Pennsylvania field before reaching its target, killing all 44 people on board.

The Airbus A380 and Boeing 747 listed are the largest passenger aircraft flying today, and have the largest passenger capacities. An Airbus A380 can be configured to carry 853 passengers, although a 500+ passenger configuration (with business and/or first-class seating) is more common. Likewise, a Boeing 747-400ER can carry up to 524 people, although configuration for a lower passenger count is more common. These aircraft types are frequently used for international travel.

The Boeing 737 is the best-selling jet aircraft in the history of passenger aviation. Southwest Airlines, a well-known carrier in the United States, uses 737s almost exclusively, with the 737-700 being the most commonly used 737 variant in its fleet. The Airbus A320 is a marketplace competitor to the 737 with similar characteristics, and is also in widespread use.

Several regional aircraft are listed here, which are aircraft used primarily for flights shorter than transcontinental. The Bombardier CRJ700 is a regional jet capable of common jet speeds, but with lower passenger and fuel capacities and lower cargo capacity than the other jets listed above. The Bombardier Q400 is a turboprop, a propeller driven aircraft driven by a turbine engine. It uses the same kind of fuel as the jets listed here.

Two aircraft are listed purely for historical reference. The Lockheed L-188 Electra was a turboprop aircraft introduced in 1957. It ultimately lost its market share to jets like the Boeing 707 and 737. Variants of the Electra are still in use today, like the P-3 Orion marine patrol aircraft used by the United States Navy. The North American B-25 Mitchell, a World War II era bomber, is included because (as mentioned above) one of them crashed into the Empire State Building in New York City in 1945. Although it uses aviation gasoline instead of jet fuel, the density and specific energy content of that fuel is similar to jet fuel. Calculations have been appropriately adjusted to obtain a chemical potential energy value for the B-25 with a full standard load of fuel.

Finally, we will consider a gasoline delivery tanker truck, similar to the kind of vehicle that can be found refilling the fuel tanks at any number of gasoline stations around the world. For the kinetic energy analysis below, we will assume that the vehicle weighs 80,000 pounds (36,288 kilograms), the maximum weight allowed by federal law for interstate transport. This is likely an overestimation, but it gives us a good feel for the worst-case scenario. We will also assume that, for the chemical potential energy analysis, the vehicle is carrying 12,000 gallons of gasoline, which appears to be at the high end of what a single large tank can carry. Gasoline weighs approximately 6.073 pounds per US gallon, meaning that our hypothetical tanker can carry 72,876 pounds (33,057 kilograms). The energy content of gasoline is assumed to be 132 million Joules per US gallon. This is not meant to be a specific calculation for any specific vehicle/load combination. It is meant to be a "ballpark estimate" to guide our understanding and intuition.

Here we will assume that the aircraft under consideration are at their maximum take-off weight (MTOW) and impact at a typical cruise speed for the airframe in question. In a real crash, an aircraft would burn some amount of fuel attaining maximum speed and thus would no longer be at MTOW at impact. This would reduce the kinetic energy of a crash. Conversely, aircraft can go faster than their published cruise speed by 10% or more, thus increasing the kinetic energy of a crash. (These maximum speeds are less readily available in published aircraft data, which is why they aren't cited here.) Using MTOW and cruise speed can give us a good idea of how much kinetic energy could be released in a worst-case crash.

The numbers used in these calculations can be found in a variety of sources. Online sources include aircraft manufacturer Web sites and Wikipedia, the free online encyclopedia. Accurate aircraft information can frequently be obtained from books in general publication, including children's books. Any American high school student of physics knows the classical formula for kinetic energy, and can find accurate aircraft maximum speeds and weights in open sources. There are no secrets being printed here.

In Table II we tabulate the kinetic energy that would be released, in TNT metric tons, for all of the listed vehicles in ascending order.

For comparative purposes, the gasoline delivery tanker truck is assumed to be traveling at 100 km/h, which is about 62 miles per hour. A collision with, say, a building would release the equivalent energy found in 34 kg (75 lb) of TNT, well below the kinetic energy of any of the aircraft listed here.

Generally speaking, aircraft with greater weight release higher kinetic energy, but there are some exceptions worth noting. The Bombardier CRJ700 has a faster cruising speed than the Lockheed L-188 Electra, so it has greater damage potential, even though the CRJ700 weighs approximately 60% of what an Electra does. This is because kinetic energy increases linearly with mass (or weight), but quadratically with velocity. Doubling the weight of an aircraft doubles the amount of damage it can do in a crash, but doubling its speed will increase the damage fourfold. A lighter jet can do more damage on initial impact than a heavier propeller-driven aircraft because of its increased speed.

Table II shows quite clearly why the impact damage on the Twin Towers by the 767s that hit them was so much greater than that done to the Empire State Building by its B-25 impact. Assuming that the aircraft in question had a similar amount of kinetic energy to that described above, the 767 impacts were roughly equivalent to more than a metric ton of explosives going off in the buildings they struck. The B-25 could have only created about 2% of that damage on impact with the Empire State Building in 1945.

Considering kinetic energy alone, choice of aircraft design can make a huge difference in potential damage from a crash. Note that in the September 11 attacks, none of the aircraft

TABLE II. Kinetic energy of various vehicles.

Vehicle Type	Maximum Passenger Capacity	Maximum Weight (kg)	Cruise Speed (m/s)	K (tons of TNT)
Gasoline delivery tanker truck	2	36288	27.8	0.00336
North American B-25 (bomber)	6	19000	103	0.0241
Bombardier Q400	80	29260	185	0.121
Lockheed L-188 Electra	98	51256	167	0.171
Bombardier CRJ700	78	32999	230	0.210
Boeing 737-700	148	70080	230	0.445
Airbus A320-200	180	78000	230	0.495
Boeing 757-200	234	115680	236	0.774
Boeing 767-200	290	142880	254	1.10
Boeing 747-400ER	524	412775	254	3.19
Airbus A380-800	853	569000	263	4.71

used in the attacks carried more than 81 passengers. Smaller aircraft could have been used for these flights, which would have greatly reduced the damage caused. For example, had a 737-700 been used, there might have been less than half the damage. Had even lighter aircraft been used, similar to the CRJ700, Electra, or even the Bombardier Q400, initial impact damage might have been less than a fifth what it actually was.

Table II also shows alarming kinetic energy levels for the jumbo jets, the Boeing 747 and the Airbus A380. A 747 can produce damage equivalent to approximately 3 metric tons of TNT in a crash. For the A380, the damage equivalent goes up to almost 5 tons. In other words, a jumbo jet can be approximately 3 to 5 times more devastating at initial impact than the 767s used in the September 11 attacks.

Table III shows the chemical potential energy (CPE) for a full fuel load for the listed

TABLE III. Chemical potential energy in a full fuel load.

Vehicle Type	Maximum Passenger Capacity	Maximum Fuel Load (L)	Maximum Fuel Load (kg)	CPE (tons of TNT)	K/CPE
North American B-25 (bomber)	6	3687	2658	29.7	0.0113%
Bombardier Q400	80	6526	5221	53.7	0.225%
Bombardier CRJ700	78	11028	8822	90.8	0.231%
Lockheed L-188 Electra	98	20628	16503	170	0.101%
Boeing 737-700	148	26020	20816	214	0.208%
Airbus A320-200	180	30190	24152	249	0.199%
Boeing 757-200	234	43490	34792	358	0.216%
Gasoline delivery tanker truck	2	45420	33057	379	0.000888%
Boeing 767-200	290	63000	50400	519	0.213%
Boeing 747-400ER	524	241140	192912	1985	0.161%
Airbus A380-800	853	323546	258837	2663	0.177%

aircraft. Note that the B-25 bomber has been included in the list, even though it uses a different kind of fuel (aviation gasoline) than the other aircraft. Computations for that airframe have been adjusted appropriately to account for aviation gasoline's lower density (0.721 kg/L) and higher specific energy content (46.8 MJ/kg). Again the aircraft are ordered by energy from least to greatest.

Here the correlation is simple. The greater the amount of fuel an aircraft is carrying, the more chemical potential energy it can release during or after a crash. Passenger aircraft with low fuel capacities, like the Bombardier Q400 and CRJ700, carry the least amount of chemical potential energy in their fuel and pose the least risk. Those with the greatest fuel capacities, the jumbo jets, can release the most chemical energy and pose the greatest risks. The Airbus A380, with a passenger capacity of approximately 10 times that of the

Bombardier Q400, has a potential for disaster from its fuel load of more than 50 times that of the Q400. The explosive equivalence of a jumbo jet with full tanks can be measured in kilotons, comparable to the yield of some of the smaller nuclear weapons that governments have produced. The nuclear bomb that the United States dropped on Hiroshima at the end of World War II released only 4 to 5 times as much energy as fully-fueled Airbus A380 could in a crash.

Note where the gasoline delivery tanker truck sits, right in the middle of the table. In terms of maximum risk from fuel fires, narrow-body jets like the 737, A320, and even the 757 are slightly safer than the gasoline delivery tanker truck with a full 12,000 gallon tank trailer. Smaller aircraft like the Q400 and the CRJ700 present substantially less risk from fuel fires than the gasoline delivery truck. A crashed Q400 or CRJ700 might produce about a fifth or a third as much damage from burning fuel, respectively, as a tanker truck accident could produce.

The final column of Table III shows the ratio of the kinetic energy (tabulated in Table II) to the chemical potential energy (tabulated in Table III). This ratio gives us a rough idea of how much fuel must ignite at some point during the crash or in its aftermath to yield the same amount of damage that the impact of the initial crash did. Note that this number in all cases is a small fraction of a percent, under a quarter percent for all the cases discussed here. The actual amount of fuel that ignites during and after a crash will depend on environmental factors and other particulars of the crash, but it is not difficult to imagine circumstances where one quarter of a percent of the fuel aboard an aircraft ignites either during a crash or shortly thereafter. This ratio helps emphasize that as damaging as impact can be, with a yield similar to the explosion of tons of TNT for larger passenger aircraft, fuel carried by a crashing aircraft represents a far greater danger.

DISCUSSION

From the data above we can better understand the comparative risks of the various types of aircraft in service today in US skies. Here are some generalizations that are worth considering in future efforts to better engineer our air transport system.

Aviation fuel is the greatest source of overall risk in any crash, as it contains more energy overall than the kinetic energy of an aircraft. There is great variability in the damage the fuel can do because it is difficult to predict how much will ignite during and after a crash, but it takes only a fraction of a percent of an aircraft's fuel to ignite to create as much damage as the initial impact. To reduce the risk from terrorism or accidents the greatest amount, we must reduce the amount of fuel aboard each flight.

There are many possible strategies to reduce fuel load. An aircraft that is lighter overall requires less fuel to accelerate to its cruising speed, thus lowering the overall need for fuel in a flight. To reduce overall aircraft weight for a passenger flight, one could simply eliminate air cargo other than passenger baggage from the aircraft.

Many airlines, known as combination airlines, have a mixed cargo and passenger business model that relies on using the same aircraft at the same time for both purposes. Cargo space not used for passenger baggage is resold to carry freight. Perhaps for this reason, combination airlines tend to fly aircraft with greater passenger capacities than other carriers, which also gives them an increased ability to carry cargo. Combination airlines frequently charge checked baggage fees ($50 for the first bag is not unusual) that encourage passengers to bring carry-on luggage instead, thus freeing up space for air cargo and increasing air cargo revenue. One can easily imagine that combination airlines can earn more revenue from packages than from passengers for some flights. If so, it is to the advantage of combination carriers to maximize their aircraft size for many routes, even if the passenger load doesn't warrant it, to increase air cargo revenue.

This mixed business model has an unintended side effect of making combination airlines greater targets for terrorism in general. The larger aircraft they fly carry higher numbers of passengers and, proportionally, cargo and fuel. In addition to maximizing the direct casualties of an incident on the aircraft itself, the planes are also capable of greater damage on the ground. It is easily imaginable that for these reasons, two combination airlines, United Airlines and American Airlines, were targeted by the Al Qaeda terrorists for the September 11 attacks. Combination airlines were also targeted for the failed "shoe bomber" attack (American Airlines) and "underwear bomber" (Northwest Airlines) attacks thwarted by passengers.

Not all airlines in the United States use air freight to the extent that widebody and jumbo jet owners do. For example, Southwest Airlines and Alaska Airlines (among others) fly Boeing 737 and smaller aircraft exclusively, which have lower passenger loads but also lower cargo and fuel capacities. Airlines like these were not targeted at all for the September

11 attacks or any of the smaller plots since then. They have also avoided the bankruptcies that have affected all of the terrorism targets listed above.

Passenger aircraft weight should be reduced to minimize kinetic energy as well, which causes damage during initial impact. Kinetic energy is directly proportional to the weight of the aircraft, so reducing weight directly minimizes impact damage. As an example, assume that the 767 flights that struck the Twin Towers had been Boeing 737-700s instead of 767-200s. The 737-700 has similar range to the 767-200, as well as sufficient passenger capacity to have carried the passenger loads of the hijacked 767s. The 737-700 is notably different than the 767-200, however, in that it has approximately half the maximum takeoff weight of the 767-200. In a crash situation, as the calculations in Table III above show, this mass difference can mean less than half the impact damage. The reduced mass also means reduced fuel load, which leads to a similar reduction in damage potential from burning or exploding fuel, as Table III shows. Such damage reductions might have made a huge difference in the casualty count from the September 11 attacks.

Substantial reductions in overall damage (i.e. damage caused by both kinetic and chemical potential energy releases) can also be obtained by reducing maximum aircraft speed, for several reasons. Kinetic energy is proportional to the square of velocity, so reducing speed can create more significant reductions in impact damage than reducing weight alone. For example, cutting aircraft mass in half is needed to reduce kinetic energy by half, but a mere 30% reduction in speed will have the same effect. Reduced speed can result in significant fuel weight reductions as well. Drag, the aerodynamic force that opposes an aircraft's forward motion, tends to be proportional to the square of an aircraft's speed. An aircraft with reduced speed will have substantial advantages in fuel economy, which allows the aircraft to carry less fuel and decreases its damage potential even further.

Here is an example of how reduced speed can reduce maximum overall damage. Compare the Bombardier Q400 and CRJ700 regional aircraft, passenger aircraft produced by the same manufacturer. They have similar passenger capacities and service ranges. The CRJ700 can fly about 25% faster than the Q400, but to do so it makes large crash safety compromises. A CRJ700 can cause about 75% more initial impact damage than a Q400 because of its increased kinetic energy. The CRJ700 also has a fuel capacity almost 70% higher than a Q400, which means that after a crash, its chemical potential energy can cause almost 70% more damage. Although the CRJ700 still has safety advantages over aircraft like the Boeing and Airbus aircraft studied here, it should still be noted that increasing aircraft speed by even small amounts results in huge increases in potential for destruction from both fuel and impact damage.

The data above for chemical potential energy also helps us understand aviation disaster risks in terms of an everyday hazard, gasoline delivery tanker trucks. In the decade since September 11 passenger aviation security has been frequently discussed and changed, but there has been little discussion of the risks associated with gasoline transport. In the US, accidents involving tanker crashes and spills are more common than large aviation disasters, and more of us have had firsthand experience with these kinds of disasters or their effects. We are more likely to have an understanding of the risks involved. With our informed intuition, we can do a simple cost-benefit analysis and determine that the fire risk from gasoline delivery tanker trucks is acceptable. We fill our car's fuel tank at the gas station even if a tanker truck is there making a delivery, and we don't worry much about a disaster occurring. For many types of aircraft, the risks of a terrorist incident in passenger aviation are substantially lower than those associated with motor vehicle fuel delivery trucks. This is an important insight to remember when making aviation security policy decisions.

SECURITY, SAFETY, AND FREE MARKETS

By calculating kinetic energy and chemical potential energy for aircraft used in passenger service, we can obtain an understanding of the destructive capacities of those aircraft. We can then compare those destructive capacities with one another and with those of better-known hazards, like gasoline delivery tanker trucks, thus allowing us to do better risk-reward calculations for passenger aircraft. For the most commonly used aircraft in American passenger aviation, like the Boeing 737, the overall disaster risk is less than that of a worst-case tanker truck accident. Many passenger aircraft in common use today, like the Q400, pose substantially less risk than that.

With appropriate risk data, it is easier to assess the need for security measures now in use, including invasive passenger screening. If we accept the idea that the scope of potential disasters is limited and small, at least for specific aircraft types like the 737 and others listed above, it may be worth considering the potential value of allowing travelers who choose to fly on these aircraft to avoid the current scanning and pat-down requirements that are far and away the most problematic aspects of current airport security measures. Traditional magnetometer-based passenger screening (i.e. metal detectors) can be used instead, as it has proven itself to be cost-effective and most passengers have little issue with screening from magnetometers.

If lower-risk aircraft have reduced screening requirements and the flying public understands this change, market forces will come into play and can help dictate the future requirements for the passenger air transportation system. Given a choice, many passengers may choose to fly on lower-risk aircraft with reduced screening requirements, thus creating more demand for these aircraft. Demand for flights on high-security aircraft would decrease, and these aircraft might eventually be retired from passenger service.

If we view uniform, aggressive screening as unnecessary for lower-risk aircraft, we must also view imposition of such screening as a type of subsidy for operators of higher-risk aircraft. Airlines with better security and safety practices are unable to offer an improved travel experience over that of their higher-risk rivals, which brings more business to higher-risk airlines. It should be noted that higher-risk combination airlines appear to have solvency issues that lower-risk airlines do not have. United, Northwest, Delta and now American Airlines have all started bankruptcy proceedings since the September 11 attacks. Lower-risk carriers like Southwest and Alaska have not had these financial problems. Subsidizing higher-risk airlines by imposing high-security on lower-risk airlines may simply be forestalling inevitable financial problems associated with bad business models.

Having better understanding of specific aircraft risks will put pressure on airlines from other sources that could create positive changes in the aircraft fleet. Public perception of aircraft risk would certainly influence the outcome of legal actions against airlines in the future. If higher-risk aircraft increase the likelihood of a finding of negligence by a jury in a potential lawsuit, airlines risk bankruptcy in the event of a disaster if they continue to rely on these aircraft. Insurers might decide that high-risk airframes should cost much more to insure, which could pressure airlines to switch to other aircraft types.

The data above shows that it is worthwhile to end the mixed passenger and cargo business model used by combination airlines like United Airlines and American Airlines. Combination airlines have been the exclusive targets of modern terrorist plots, and with good reason. Combined airlines use heavy, fuel-laden aircraft that are much more destructive in the event of an accident than the aircraft used by more passenger-focused airlines like Southwest

Airlines. Cargo also introduces an extra attack vector, the cargo itself, for terrorists to try to exploit. By limiting cargo on passenger aircraft to passenger baggage only, overall aircraft weight can be reduced, which leads to proportional reduction in kinetic and chemical potential energy that can cause devastation in the event of a crash, either intentional or accidental. That policy would also eliminate the most tempting targets for terrorism in American skies.

SUMMARY

Simple physics allows us to categorize passenger aircraft by their potential destructive power. Widebody and jumbo jets represent the greatest threat to passengers and bystanders alike, partly due to their high speed and weight, but mostly due to their high fuel capacity. Many other aircraft commonly in use have potential destructive risks comparable to those associated with motor vehicle fuel delivery, which society generally deems acceptable. Substantial reductions in potential damage can be obtained by using aircraft with lower speed, lower fuel capacity, and lower weight. Existing aircraft designs, already in service, can be used to replace other aircraft types and thus reduce risk.

The combination airline business model ultimately needs to end for safety reasons alone. Simple market forces can bring about that change by themselves provided that the public, insurers, and investors all have appropriate information regarding aircraft risk potentials. Providing passengers with incentives to use less-risky aircraft, like simpler screening for lower-risk aircraft, may be sufficient to provide permanent improvements in passenger aviation security far in excess of what passenger scanning alone can accomplish. Reducing screening for less-risky aircraft types can also be viewed as ending a government subsidy for businesses with questionable businesses models.

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