Concorde's Tyres

Disaster, Law, and Ontology

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Abstract: This article explores the Concorde crash of 25 July 2000, seeking to show how law and regulation do crucial ontological work in the maintenance of commercial flight, and likely other aspects of modern techno-social arrangements. I argue that law and regulation cannot be seen as an exteriority, constraining and shaping the production of technology, but should be viewed as a component in the production of a physico-legal reality that a machine embodies. The Concorde disaster, by this logic, happened when that reality proved to be inadequate. It sparked a physical redesign of the aircraft, but also an intertwined effort to repair it normatively. Commercial flight is thus a total phenomenon comprising physical and social laws. This, I suggest, is the ontological significance of law and regulation in the production and maintenance of airliners.

Keywords: aircraft, law, modernity, ontology, technology, universe

This article is about the ontological work that law does in complex and risky technical systems. In it, I argue that law is ontologically necessary for the existence of such systems. I make this argument in the context of the crash of a Concorde close to Paris in 2000. This is a brief account of the accident:

> At 14:42 on 25 July 2000, Concorde F-BTSC, serving Air France flight 4590, was cleared to take off on runway 26R at Paris Charles de Gaulle airport. About a minute later, the aircraft attained V_1, the speed at which take-off cannot be aborted. Six seconds after V_1, tyre number two, part of the left main landing gear, ran over a metal strip[1] that had been dropped on the runway by an aircraft that had departed previously. The tyre burst, propelling a 4.5 kg chunk of rubber into the left wing. A severe rupture occurred in the number 5 fuel tank, closest to the burst tyre. Fuel began to pour out and soon caused a massive fire beneath the left wing.
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> The left-hand engines now began to lose thrust. This was most likely due to their ingestion of a combination of tyre fragments, leaking fuel, and hot gases from the fire. With only the right-hand engines operating

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> properly, the aircraft's track down the runway began to veer to the left and it threatened to leave the tarmac. Almost immediately, the captain began raising the nose for take-off, even though the airspeed was below what was needed for the aircraft to fly safely.
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> Eleven seconds after the tyre burst, the aircraft was airborne. Informed of the flames behind the aircraft by the control tower, and apparently believing that one of the left-hand engines was on fire, the crew shut it down. They then attempted to retract the landing gear, which they found to be impossible. The aircraft had attained an altitude of 30 m but was flying much too slowly to climb away from the airport.
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> Without sufficient speed to climb, or enough height to turn back to Charles de Gaulle, the crew attempted to reach the nearby Le Bourget airport for an emergency landing. The intensity of the fire under the left wing, however, was progressively destroying the flight control surfaces. Now, the remaining left-hand engine completely lost thrust – the other was already shut down. Only the two right-hand engines were operating, unbalancing the plane. The aircraft became uncontrollable, banking sharply to the left and adopting a nose-up posture. The crew shut down the remaining engines, perhaps in an attempt to control the bank angle. Without thrust, the aircraft stalled less than 50 m from the ground, without any possibility of recovery. The crash killed all 109 people on board and a further four on the ground. The flight had lasted for about ninety seconds.

This article draws on a number of sources but takes most of its substantive material from the English translation of the air accident report on the disaster, produced by the Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile, hereafter the BEA, in collaboration with the Air Accident Investigation Branch from the UK and with input from the National Transportation Safety Board of the USA (BEA 2002).

The summary of the accident sequence with which I began this article is based on that report. The report formats the disaster in a particular way, according to the interests and aims behind the report-making process (Rasmussen et al. 1994). The BEA describes its mission as being to 'further improve aviation safety and keep the public's confidence by means of safety investigations and studies carried out in an independent, effective and impartial manner' and to 'capitalize and promote the safety data and lessons learned by the BEA to prevent future civil aviation accidents' (BEA n.d.a). These aims are pursued in relation to accidents and incidents.[2] A BEA accident investigation is triggered when the agency is notified of an accident and deals specifically with that accident until the investigation concludes (BEA n.d.b). The account of the disaster presented in the BEA report treats it as a single, identifiable happening, and is designed to enable lessons to be learnt and changes made to prevent a recurrence of similar accidents (Strauch 2006).

Being neither a historian nor a specialist in documentary sources,[3] I have treated the BEA report as though it were a kind of source material with which I am familiar, an extended set of field notes. This means that I accept the content of the report, while reviewing it in part, and consider what it does constructively by comparing it with other materials to build up a picture of meaningful relationships.

The relationships that this article focuses on are between technical devices, in this case aircraft, and laws, rules, and regulations. The connections I am particularly concerned with are those that *make commercial flight possible*. The argument has three main parts. The first is theoretical. Following Mol (2002) and Law (2002), I argue for symmetrical treatment of things and representations of things as performances (Law's term) or enactments (Mol's) that constitute realities. Applying these insights to law, I argue, with Strathern (1985), that rules should not be seen as representations organizing social life, but as the basis of performances. In the second part of the argument, I show how aircraft design similarly works to perform the regulatory standards for the certification of aircraft. This performance, in turn, enacts a reality in which some kinds of events or risks are included, while others are not: an aircraft performs certain modes of failure. I argue that the Concorde accident can be read as the point at which the reality enacted by the aircraft proved to be inadequate in the face of an unprecedented failure mode. In the final sections of the article, I discuss the way in which this breach in Concorde's design reality was repaired, arguing that this process should not be understood as a technical matter only, but as a hybrid of law and engineering. The central claim I make is that regulation is *ontologically* necessary for flying: flight is a total phenomenon, mobilizing both physical and normative laws.

Reality Performed

The main concerns of this article echo an argument made recently by John Law (2015). He argues that the dominant institution of Northern knowledge is the idea of the universe. This is a *single container* for everything that exists. From the point of view of history, it is passive, a background to human agency (cf. Chakrabarty 2009). From the perspective of the physical sciences, it represents the causal forces that produce all phenomena. Most importantly, the universe is never something that people *do*: it *is*, whether as a mere background or the source of the principles of causation.

STS scholars such as Law have long been arguing that modern techno-scientific practices do not work on materials, forces, or principles that precede them, but actively produce them (Callon 1986; Latour 2004; Law 2002; Law and Hassard 1999). If reality is a product of techno-scientific activity, it follows that, in an objective sense, it is neither singular, nor a container for human action. As a result, it is not a constant relative to which human knowledge and activity can be assessed.

Law (2002) has applied such ideas to complex machines with his work on the abortive TSR-2 military aircraft. He uses the language of performance to describe the process of conception and design of the aircraft, and dwells at length on a brochure, advertising the aircraft to officials, that was produced by the manufacturer, British Aircraft Corporation. Law argues that each different presentation of the aircraft – a schematic representation of the fuel system, a map showing its operating radii from different bases, artists' conceptions of the plane in flight and on the ground – *performs* it. Telling such 'stories', he argues, 'helps to perform the world':

> This means that in a … performance, reality is staged. And such staging ensures that, everything else being equal, what is being performed is thereby rendered more obdurate, more solid, more real than it might otherwise have been. It becomes an element of the present that may be carried into the future. (Law 2002: 6)

To be clear, what this approach consists in, essentially, is an *equalization* of the value of speech and writing, on one hand, and materials, devices, and actions on the other. Mol (2002) makes this position clear. A straightforwardly perspectival or relativist approach to the relationship between representation and reality – this machine, or illness, or what have you really exists; here's what different people think about it – firmly distinguishes symbols from the material world and reality from representation (Strathern 1995). Materiality is tasked with being real, representations carry the load of difference (Viveiros de Castro 2015). Institutionally, physical scientists monopolize true knowledge, while human scientists study culture (Ingold 2000). That distinction is maintained, and even strengthened, by a postmodern or poststructural turn to representation. This position holds that machines, or illness, or whatever, come into existence through representation. Physical scientists, just as much as their colleagues in the human sciences, and everyone else for that matter, are in the business of bringing representational worlds into being (Foucault 1994). This position endeavours to equalize representations among themselves but does not produce an equality between representations and material things. Materiality is simply excluded from the analysis (Butler 1989). The performative approach advocated by Law and like-minded scholars (Latour 2005; Law 2002; Mol 2002) works by making *acts* of representation appear as material happenings, things that people do, while insisting that material things perform the stories in which they are involved and carry them forward into the future (Haraway 2016; Latour 1993). The result is an ontological plurality that consists in deliberately effacing the difference between representation and reality in favour of a logic of situated practice as performance or enactment.[4]

The implications of this approach for understanding law are important. Strathern (1985) observes that law and regulation are intuitively understood in terms of control. Specifically, she argues that the notion of law implies that one kind of behaviour, activities concerning rules, functions to control other forms of behaviour. There is thus a hierarchy between these activities. This hierarchy, she argues, is formatted on the same lines as representation. The control that law seems to exert over social life stems from the fact that its role is to *represent* social life in a particularly authoritative, organizing way.[5] Law may thus appear as an imposition (Comaroff and Comaroff 2006; Lawrence 1969) – although it may equally be represented as an experimental, creative process of (re)describing social life (Demian and Rousseau 2019; Doughty 2015; Strathern 2003). In whatever way it is imagined, where representation is thought of as a distinctive form of activity, more abstract and authoritative than practice, then law and what it regulates can and must be distinguished. That distinction will necessarily be patterned on the relationship between a sign and what it signifies, and the relationship between law and social life will be fundamentally representational or *epistemological* in character (Mol 2002).

The notion of performance I drew from Law (2002) and Mol (2002) above, however, collapses this representational relationship. Rather than occupying a different 'level' to the practice that it describes or defines, law becomes a practice among others (Latour 2010).[6] To the extent that a domain of practice is 'regulated', I argue that we should see regulatory representations not as guiding or organizing practice, but as *involved in practices* as a component of their performance. Indicatively, aircraft engineers talk about aircraft being made to *embody* regulations.[7] In the case of aircraft, and Concorde's tyres specifically, I argue in the next section that the performance of regulation is central to the production of safe, operable aeroplanes.

The Performance of Regulation

The high level of safety and reliability of civil aviation is so often remarked on, especially by people who are involved in the industry, as to be almost redundant (Langewiesche 1999). In regulatory terms, the safety of aircraft is overseen by national civil aviation authorities (the EU has its own authority as well), which certify aircraft as 'airworthy'.

This certification is made according to a set of standards. Contemporary standards are closely harmonized, with the major US and European codes being substantially identical. Among other things, certification standards specify minimum levels of structural strength for airframes, the use of appropriate materials, designs, and systems, and acceptable handling characteristics for aircraft. They also define how the aeroplane and its systems should behave in the case of certain failures. The compliance of an aircraft and its systems with certification standards is demonstrated by various experimental tests – both laboratory bench tests and whole-aeroplane flight tests – as well as being subjected to various kinds of statistical failure analysis.

Where a certificate is issued, it represents a *prediction* that the aeroplane will operate with a one in one billion chance of catastrophic failure, which is to say it will fly safely 99.9999999 per cent of the time (Downer 2017: 236 n. 13). Coming to that prediction about an aircraft is problematic, however, as Downer (2017) demonstrates. To test a system to demonstrate that it will fail once in a billion working hours would require 144,000 years – and even with parallel tests, it is not possible to demonstrate that level of reliability in an empirical sense. It is therefore usually established by a calculative practice. Components whose service histories and rates of failure are known are combined in parallel into systems with a level of redundancy. The system as a whole can meet the regulatory threshold if the chance of *all* of the redundant systems failing at once is less than one in a billion.

That prediction, as Downer argues, is in principle deeply questionable. Importantly, it is hard to establish the relevance of a component's history for a future application. As the basis for a calculation of reliability, using history in this way presumes that the service record of a component used in one context will be the same as that of the same component in a wholly different system. The same is true of laboratory testing – for example the bird-strike tests that Downer (2007) also discusses. In these tests, turbine engines have chickens shot into them using a giant airgun to make sure they won't disintegrate in a dangerous way if they ingest birds in flight. However, there are serious doubts, even among people involved in these tests, about whether they adequately simulate a real bird-strike incident, and therefore how relevant their results are for the actual safety of jet engines.

Given these doubts about the actuarial and experimental basis of certification and the predictions of reliability it involves, Downer questions why it is that safety estimates for airliners appear to be so accurate, and the aircraft themselves so safe. He argues that it is a result of a deep conservatism in airliner design, which has remained largely stable since the introduction of passenger jets.[8] Because there are so many airliners, and they fly so much, a great deal of experiential and statistical knowledge exists about their performance and the way they behave in different circumstances. Testing an aeroplane and determining whether it is safe is therefore less about the results of the tests themselves, whose relevance to real-world operations is not obvious, and more about the likeness of a new machine or system to an older, well-understood one:

> All that is needed to predict the reliability of a new system is compelling evidence that it is substantially similar to a previous system, combined with good data on how often that previous system has failed in the past. (Downer 2017: 240–241)

The point here is that aircraft are, essentially, *reiterations* of a basic pattern (Butler 1990): they reference and perform one another in establishing their reliability in terms of airworthiness regulations. Aircraft embody past experience of designs, components, and systems, as well as previous accidents (BEA 2002: 178; Downer 2017; Owen 1998).[9] The past is gathered into the calculative practice by which safety is prospectively demonstrated, and regulatory frameworks are embodied in working machines. As the current European airworthiness standards have it: 'The aeroplane may not have design features or details that *experience has shown* to be hazardous or unreliable' (European Aviation Safety Agency 2007: CS-25.601; the American equivalent FAR 25.601 has 'airplane' but is otherwise identical). In other words, aircraft perform their compliance with certification standards by being like other aircraft.

Concorde's Tyres

This pattern of intense reference to previous designs is evident in Concorde's tyres and landing gear. Taken as a whole, Concorde was a radically different kind of design to other aeroplanes of the time, and quite different to any jetliner designed since. Dudley Collard, an engineer with Aerospatiale involved in the Concorde project, concurred with Downer in remarking:

> The development of a new civil transport normally relies heavily on extrapolation of existing knowledge. On the CONCORDE where this was not possible it was necessary to adopt a completely new, unconventional configuration. (Collard 1991: 2622, capitalization in the original)

On this basis, Downer (2017: 242) is sharply critical of Concorde: 'Regulators were wrong about its safety and should have refused to approve it on the grounds that its design was too unprecedented.' As it happened, whole new testing regimes had to be developed in order to certify it ('Proving the Concorde' 1969; Chevalier 1974; Harpur 1971).

The aircraft's landing gear, however, was generally conventional. Collard (1991: 2635) tells us:

> The landing gear on the CONCORDE is conventional … In addition to a normal twin wheel nose and four wheel main gears there is a small twin wheel tail unit that fulfills the rôle of the tail bumper on a subsonic transport aircraft. (Capitalization in the original)

Certainly, elements of the aircraft landing gear were new. The tyres had to be safe for landing at an unusually high speed, and advanced use of composite materials were a feature of the braking system. New conditions were also established for certification, which allowed the use of reverse thrust to be included in the overall assessment of the aircraft's stopping power (Collard 1991: 2636). From his perspective as a Concorde engineer, however, Collard (ibid.) claims that, despite these innovations, the aircraft had a 'basically classic landing gear layout'. At least from his perspective, the aircraft's landing gear seems to be another instance of a new aeroplane referencing the past – and the tyres were duly certified. The type's American-type certificate (Federal Aviation Administration 1979: 6) has a line specifying that for certification purposes 'Main and nose-wheel tires are required in accordance with Concorde Specification No. 459579/77'.[10]

The innovations involved in Concorde's design, however, strained the aircraft's reiteration of a 'basically classic landing gear layout'. This is clearly illustrated in the BEA report's discussion of previous tyre failures (BEA 2002: 98–102). Prior to the Paris crash, the BEA found fifty-two documented tyre failure incidents affecting the type, which the crash investigators reviewed (ibid.: 94–98).

The most serious of these tyre failures involved a tyre burst on take-off at Washington Dulles airport in 1979, the year of Concorde's

American certification (BEA 1980, 2002: 96–97; Grubisich and Mansfield 1979). In that incident, the burst tyre released fragments of rubber, as well as breaking loose small components of the landing gear. Together, these caused damage to the engines and hydraulic systems, and made multiple penetrations of the wing fuel tanks, although none were as serious as in the Paris crash. The investigation into the Washington incident determined that the tyres should be reinforced so that they would bear twice the expected load (rather than the 1.5 times demanded by regulations), and the wheels were strengthened so that the aeroplane could take off and land without any inflated tyres (BEA 1980). New inspection routines and a tyre pressure indicator system were also introduced. These measures reduced the frequency of tyre bursts but did not completely prevent them. However, this was not thought to be a serious problem, since the damage caused in the Washington incident did not threaten the plane's ability to fly and land. The leaks from the fuel tanks were small enough not to present a serious risk of fire and the main threat to the aircraft in the 1979 incident seemed to be from the damage to the hydraulics (ibid.). More ambitious – and expensive – measures, such as reinforcing the fuel tanks to avoid damage, were discounted as excessive (Chittum 2018).

The modifications made to Concorde's tyres in the aftermath of the 1979 Dulles incident reinforce Downer's point about the role of experience, rather than experimentation, in determining aircraft safety. Concorde's tyres *perform* their service history.

In certification tests, the aircraft's tyres had to demonstrate the ability to withstand 1.5 times the maximum allowed service load of the aircraft. For these tests, the wheel and tyre, filled with water, were attached to a special rig, a truck-bed loaded with concrete beams. This test was entirely static – the truck was not required to move. As with the bird-strike tests that Downer discusses, this test does not represent a realistic simulation of a tyre burst in service. If it occurred on take-off, as the designers were surely fully aware, a tyre burst could happen with the wheel and tyre spinning at enormous speeds and might eject large bits of tyre against the aircraft. After the fact, the investigators into the Paris crash criticized 'the inadequacy of the tests in the context of certification' (BEA 2002: 179), especially their failure to test for, or perform, the dynamic properties of a tyre failure. However, seen from the point of view of Downer's argument, the non-representative static loading test, in the context of the history of aeroplane tyres, evidently worked for regulators as a proxy for performance in service.

Concorde's tyres after 1979 likewise enfold experience. This was the experience of the 1979 incident, which gets built into the aircraft.

After 1979, the strength of the tyres was increased so that, in the static test, they would bear twice the service load. Now strengthened, they embodied an experience of the risk that was made evident in the Dulles incident. However, the lack of any other protective measures taken was also a reflection of that experience. The decision not to protect Concorde's fuel tanks in the aftermath of the 1979 incident can be connected directly to the fact that the Dulles tyre burst only released small pieces of tyre and resulted in limited damage to the fuel tanks.

The point is that Concorde's tyres were designed and then developed with certain kinds of failure in mind: they *performed those modes of failure*. The tyres enacted a kind of reality in which they could, and might well, burst, since they had done so in the past. In the reality performed by the tyres, that burst would be of a particular kind. It would mainly result from wear and friction forces and eject relatively small pieces of debris, which might damage fuel tanks and necessitate an emergency landing, but which would not seriously compromise the safe operation of the aircraft. What this means is that the aircraft's tyres perform reality in specific ways. On one hand, the 1979 Dulles incident serves as a model for future tyre failures. On the other, tyre bursts in certification tests are wholly static phenomena, in which the ejection of large pieces of tyre from a spinning wheel does not figure. Taken together, the Dulles incident, the changes to Concorde's tyre design, and the static truck-bed test were sufficient to enact the safety of Concorde's tyres as a critical subsystem of the aircraft landing gear. Through these enactments, Concorde in turn performed its compliance with airworthiness regulations.

On the day of the Concorde disaster, the reality performed by Concorde's tyres held together until six seconds after the plane reached V_1. At that point, Concorde's left main landing gear ran over the metal strip lying on the runway. This strip, as it happened, was bent in such a way that it lay on edge. At the time, Concorde was travelling at 75 m/s, rather more than 200 mph, and weighing something in the region of 185,000 kg. The strip cut through the inboard front left tyre, almost right across its width. The tyre burst violently, ejecting a 4.5 kg chunk of rubber. This piece was recovered by investigators from the runway (BEA 2002: 60).

It was the investigators' examination of this piece of rubber that suggested how the tyre had been destroyed – the damage to the tyre matched the contours of the metal strip. That conclusion was then confirmed in a series of experimental tests. The first of these tests used the same kind of rig used for static tyre certification tests, but the truck-bed was *rolled* over a metal strip of the kind recovered from the runway (BEA 2002: 97–98). This test showed how the strip would cut right through the tyre, leading to a violent burst, even at the low speeds possible with the test rig. The second test saw a Concorde wheel and tyre spun on a different test rig against a static drum, while a metal strip was inserted between the tyre and the drum. This high-speed test, too, caused a violent tyre burst, which ejected fragments, similar to those found on the runway (ibid.: 101).

These new tests, then, performed a reality in which violent tyre bursts, ejecting large pieces of debris, were both possible and significant. This was a reality quite unlike that embodied in static tests and formatted by the 1979 incident at Dulles – the failure modes that Concorde's tyres had enacted up until that point. Whereas Concorde had been a safe aircraft in a world without dangerous tyre incidents, the tests performed by the investigation relocated the aircraft in a wholly different reality in which its tyres were suddenly dangerous. The crash enacted, retrospectively, this new reality.

From this point of view, the Concorde crash, while it can be thought of as unfolding in practical terms along the lines of the BEA report, can also be understood as having been caused when Concorde *exited the reality that the aeroplane performed* through its design and certification.

Shock Waves and Fuel Displacement

For crash investigators, certifying agencies, operators, and manufacturers, the investigation of a crash must thus involve reconstructing a single situation that can include both the aircraft in question and the specific train of events that led to disaster. The stakes were raised after the Paris crash, since the small surviving Concorde fleet – seven British Airways and six surviving Air France machines – were grounded in the aftermath of the accident (BEA 2002; Chittum 2018). However, harmonizing the continued existence of a type of aircraft with a given disaster sequence is problematic since, by definition, the reality for which the aircraft was designed and which it embodies does not include the event that destroyed it. Air accident investigations, then, re-enact disasters so that they can re-enact expensive aeroplanes back into compliance with regulation, and back into the air.

To investigate major aviation accidents, different specialists work on different aspects of the accident. In the case of the Concorde disaster, the investigation was organized around different teams, which examined the site and wreckage, the aircraft, systems and engines, preparation and conduct of the flight, personnel information, flight recorders, aircraft performance, witness testimony, and previous incidents (BEA 2002: 15). The materials on which the BEA report is based are drawn from a bewildering array of sources. The report encompasses a few photographs of the stricken Concorde leaving the runway as well as the testimony of eyewitnesses. Other materials are drawn from examination of the aircraft wreckage and physical signs left on the airport, at the crash site, and under the aircraft's flight path. These materials were documented as they were discovered by investigators after the crash, and later tested and analysed. There is also information from the cockpit voice recorder and flight data recorders, as well as archival sources related to the aircraft design and previous incidents involving the type. The report reviews Air France procedures for the Concorde fleet, including flight operations and maintenance, and the certification and medical histories of the crew. In addition, investigators commissioned a number of tests, both physical experiments and computer simulations, to test hypothetical accident scenarios. The range of different types of source material contributing to the report is typical of an air accident report (Strauch 2006) and other reports into accidents involving complex technical systems (Perrow 1999).

With such different forms of information or data – speech and tyremarks, bits of wreckage and bits of text – one of the key functions of the accident report is to organize varied materials so that they cohere. This is done in a number of different ways, for example by comparing maintenance procedures to the state of recovered aircraft components, or by matching sounds captured by the cockpit voice recorder to the position of switches and other controls in the cockpit. Leaving aside the question of accuracy, it is important to note that the coherence of an air accident report is a textual achievement (cf. Law 2002). The report makes a single, narratable happening out of a diverse body of potentially incommensurable traces.

This assemblage, which constitutes the causes of an accident, will always, in principle, be a surprise. An aircraft is certified on the basis that it is safe, and that safety is anchored to the assurance that no failure or foreseeable combination of failures should cause it to crash. A crashed aeroplane is always a scandal of foresight. The work of air accident investigators, then, consists in large part in the (re)assembly of a happening that can have no respectable place in the reality enacted by the crashed aeroplane – even though the crash itself necessarily casts doubt on that reality.

Air crashes, in this sense, enact a kind of 'wild' reality – where 'wild' is understood in Cronon's (1996) sense as naming something with its own proper logic that exceeds or eludes foresight. This wildness is expressed in many air disasters in the way in which they generate new phenomena that were never predicted in the design of an aircraft. This is particularly evident in the case of the Concorde disaster.

A little further down the runway from the place where the chunk of tyre was discovered, investigators found a fragment of the crashed Concorde that was soon identified as part of the skin of the lower wing that formed the floor of fuel tank 5 (BEA 2002: 61). The piece measured about 30 cm × 30 cm. It showed no signs of fire damage, so had evidently been ejected from the wing before the fire took hold. Considering what was known of the flame visible behind Concorde as it took off, the marks of first kerosene and later soot also found on the runway, and the testimony of the fuel gauges recovered from the wreckage, the investigators determined that the piece of aircraft skin from the runway corresponded well to the rupture that occurred in tank number 5.

The proximity of the tyre debris to the piece of underwing skin and the beginning of the kerosene stains on the runway showed that the tyre burst had to have caused the fuel-tank rupture. This part of the explanation was clear. The problem was that the piece of wing panel showed no signs of an impact from the outside – its outer, white face was clean and undamaged (BEA 2002: 109). Rather, it showed every sign of having been torn out of the aircraft from the *inside towards the outside*. It had not, in other words, been knocked off the aircraft by a chunk of tyre or any other debris. What was the mechanism that had ruptured the fuel tank (ibid.: 167)?

To account for the fuel tank rupture, the investigators proposed an analogy with a similar phenomenon. It was known that high-energy projectiles, such as bullets, impacting fuel tanks in military vehicles and aircraft, could cause a rupture somewhere other than the initial impact site. This could happen because an object, travelling through the air, will be dramatically slowed when it enters a denser material, such as kerosene. As it slows, it transfers its energy to its new medium. Especially when the new medium is a liquid, this energy can have two effects: it will definitely cause a high-speed displacement in the new medium, and it might set up a hydrostatic shock wave – essentially a very high-energy, high-speed displacement. Either of these phenomena, in a full fuel tank, were known to have the capacity to cause the walls of the tank to deform. This might cause damage some distance from the impact site, and, crucially, would involve a load being placed on the tank's skin from the inside (BEA 2002: 112–113).

This appeared to investigators to provide a plausible explanation for the damage evident on the piece of underwing skin found on the runway. However, it presented two problems. Firstly, the displacement or shock damage phenomenon had never before been seen in a transport aircraft. It was known from military contexts in which fuel tanks are struck with bullets or other small, very high-energy objects. The tyre fragment from the runway was large and, although it would have been ejected at speed, would have had a great deal less energy than a bullet. The burnt and melted remains of tank number 5 from the crash site showed a small penetration (40 × 10 mm in size), but it wasn't clear when or how it had been caused (BEA 2002: 111).

Secondly, the displacement and shock damage theory proved difficult to test. The investigatory team set up an experiment using a box made of the same materials as tank number 5, filled it with kerosene, and fired pieces of tyre at it using a pneumatic cannon (more usually employed for launching chickens into jet engines to test bird-strike resistance). However, they could not lay their hands on enough Concorde skin material, a special alloy called AU2GN, to make a box with anything like the dimensions of the actual tank, nor could they replicate its internal structure. To make matters worse, the huge airgun they were using to launch the pieces of tyre didn't have enough oomph to shoot the chunks of rubber at a realistic velocity. The investigators succeeded in denting their box and demonstrating that significant displacement would take place given such an impact, but not that it would result in a rupture (BEA 2002: 113–114, 167). They had rather more success using computer modelling. Using software to model the effect of a small, high-energy projectile penetrating the lower skin of tank 5, they produced a virtual hydrostatic shock, concentrated on a single joint in the tank, and exerting sufficient force to produce a rupture (ibid.: 114–117). However, this modelling was itself dependent on the rather sketchy evidence for such a penetration having taken place – evidence that seemed to discount the much larger tyre fragment that was definitely associated with the initial kerosene leak.

As far as the investigators could conclude, then, the Concorde crash was most likely caused by a phenomenon that had never been observed and could not be conclusively demonstrated to have taken place. It related to a mode of tyre destruction that was no part of the aircraft's design or certification and was a phenomenon that putatively existed entirely outside the design parameters of Concorde, or any other transport aircraft (BEA 2002: 176).[11] The investigatory report, in short, concluded that the accident happened completely outside the reality that Concorde performed.

Aftermath

On 16 August 2000, just three weeks or so after the crash, the BEA issued an interim report. This report already contained the main findings that would be published almost two years later in the final investigatory report, and which have already been described. Crucially, it acknowledged the faulty assumptions underpinning the certification of Concorde's tyres. The interim report stated that 'in-service experience' had shown that 'the destruction of a tyre during taxi, takeoff or landing is not an improbable event on Concorde and that such an event may cause damage to the structure and systems'. While acknowledging that previous events had not caused such serious fuel fires, the interim report concluded that 'the destruction of a tyre – a simple event which may recur – had catastrophic consequences in a very short time without the crew being able to recover from the situation' (BEA 2002: 177).

This clearly marked Concorde's tyres as *too risky* to operate. In the terms of the certification standards, they had become components that experience had shown to be 'hazardous or unreliable'. The next paragraphs of the August report therefore became inescapable:

> Consequently, without prejudice to further evidence that may come to light in the course of the investigation, the BEA and the AAIB recommend to the Direction Générale de l'Aviation Civile of France and the Civil Aviation Authority of the United Kingdom that:
>
> - **the Certificates of Airworthiness for Concorde be suspended until appropriate measures have been taken to guarantee a satisfactory level of safety with regard to the risks associated with the destruction of tyres.**
>
> This recommendation was immediately accepted by the airworthiness authorities in France (DGAC) and United Kingdom (CAA), and the Concordes' Certificates of Airworthiness were suspended. (BEA 2002: 177, bullet points original)

An aircraft cannot fly without a certificate of airworthiness. The disaster therefore created a situation in which a fleet of extraordinarily expensive machines – costing for storage, maintenance, and insurance, on top of the considerable investment they and their support systems represented – were sat idle in Paris and London. Something was going to have to be done, clearly, and whatever that something was needed to evade or cut through the uncertainties and minutiae of the investigation. That something would have to be the crucial work of maintaining a reality in which Concorde could fly – of recreating or shoring it up.

At one level, that something was an engineering solution to the evident vulnerability of Concorde's tyres, and the attendant risk of catastrophic fuel tank rupture. The interim report notes that the regulators, manufacturers, and operators accepted the basic findings of the investigation to date and proposed a series of fixes to the aircraft (BEA 2002: 177). These covered a wide variety of issues, including possible sources of ignition (reinforcement of electrical harnesses around the landing gear) and debris (modifications to the wheels' water deflectors), as well as directly addressing the most obvious causes of the crash.

To this latter end, new tyres were specified – a newly developed Michelin product called the Radial Near Zero Growth tyre, designed for the giant Airbus A380 (see 'Michelin® Radial NZG Technology' 2014). This tyre would accept *nine times* the static load of Concorde's (already improved) Dunlop tyres and is claimed to be harder-wearing, and more resistant to foreign object damage, than conventional aircraft tyres. It is also designed in such a way that a burst will result in the ejection of only tiny pieces of rubber, too small to damage an aircraft's skin. To go with the new tyres, Kevlar armoured liners were required for wing fuel tanks 1, 4, 5, 7, and 8 in Concorde – those that were deemed to be vulnerable to debris from the wheels.[12] These modifications were already being undertaken at the time that the final BEA report, with all its caveats and uncertainties, was finally released.

In 2001, about six months before the final BEA report into the Paris accident was released, modified Concorde aircraft returned to flight testing and then to scheduled service from London and Paris to New York (Staff and Agencies 2001). This service continued until 2003, when a combination of low profitability after the 11 September 2001 attacks on New York and Airbus's unwillingness to continue to provide spare parts led to Concorde's retirement (Glancey 2015).

Law as Ontological Agent

This conclusion to the story of the Concorde disaster demonstrates the centrality of regulation to the material fact of flight. In the immediate aftermath of the disaster, Concorde could no longer fly, since it could not be shown to operate *with the level of reliability expected of a civil* *jetliner*. The notion of 'sufficiently reliable flight' is evidently a hybrid of a physical phenomenon (flight) and a normative construct (how risky flying should be). This hybrid form is encoded in regulations and built into aircraft that perform the relevant norms as the condition of their certification.

To maintain a distinction between laws and rules as authoritative representations, as opposed to objects and practices as the material things represented, it would be necessary to distinguish sharply between physically possible flight and legally permissible flight. This distinction between *physical* and *legal* flight traces a broader one between a positive fact (this flies) and a normative injunction (this may not fly). To maintain the notion of law as representation – that is, the kind of perspectival or relativist model of the world dubbed a 'one-world world' by Law (2015) – it is necessary to keep positive facts and norms entirely separate. If norms, which are evidently variable, are allowed to have the same status as positive facts, then the perspectival relationship between signifier and signified breaks down. Instead of having a singular world on which multiple perspectives are possible, multiple norms would create multiple worlds. This multiplication of reality is exactly what seems to be happening in the case of Concorde's tyres. The regulatory shift following the 2000 accident gave the aircraft's tyres, and by extension the entire machine, a whole different set of (material-legal) capacities, without the (material) composition or qualities of the tyres changing at all.

In the terms I have adopted in this article, before the crash, Concorde's tyres performed their safety and reliability. Their safety was real in the sense of being 'an element of the present that may be carried into the future' (Law 2002: 6). This signals the ontological centrality of rules to technical systems. Merely physical flight does not exist in the context of transport aircraft. Flight is, instead, a *total phenomenon* in Mauss's (2002) terms, here mobilizing the whole spectrum of physical and social laws.

The aircraft's safety was then undone by the crash and the recommendations made by the BEA report. The disaster resulted in the transformation of tyres that were *more* reliable than the industry standard, capable of bearing twice the expected service load, into hazardous components, presenting known risks attested by experience. The reality that the tyres came to perform, what they would now carry into the future, was the risk that they presented. This meant that, although the aircraft and its equipment had not changed, it could not fly with the expected degree of reliability and safety. This meant in turn that, in its capacity as a transport aircraft, it could not fly at all.

Concorde's suddenly risky tyres now left the aircraft stranded. It was a kind of scandal or anachronism: a thing built to perform a set of norms that no longer held, embodying a reality that had collapsed. From this point of view, it resembles the guillotine that Foucault (1995) describes, hidden away inside late-nineteenth-century French prisons. For Foucault, the hidden guillotine is an icon of the effective collapse of sovereignty, as the public and ritualistic exercise of violence, in the context of a modern state whose logic is quite different (Foucault 1991). The guillotine persisted, in Foucault's (1995) account, because criminal law as a textual form retained the notion of state sovereignty, the power to kill or let live. The guillotine was hidden because, under cover of the abstract idea of sovereignty, the practices of punishment had changed and proliferated into subtle techniques of control and discipline, which had come to inhabit everyday life. The guillotine could not be done away with because it represented the founding principle of the state, but it could not be operated publicly without undoing the practices by which that state operated. Concorde, grounded after the accident, found itself in a similar position. The accident appeared to have happened in a way that was entirely outside the design parameters of the aircraft, embodying a kind of failure that was no part of the machine or the regulations it performed. As a result, the plane was, like the guillotine, superseded, instantiating a previous iteration of reality in a very concrete, and extremely expensive, form.[13]

Unlike the guillotine in modern France, however, the realities of aircraft can be re-engineered. This re-engineering, in the case of Concorde, is embodied in Kevlar fuel-tank liners, strengthened electrical harnesses in the landing gear, and new tyres. It is easy to understand such changes in purely technical terms – the new components are better than the old ones, and so make the aircraft safer (Downer 2011). That reading, however, presupposes that safety itself is a positive feature of technology. It neglects the regulatory or normative fact that the aircraft was safe *before* the accident. If this form of safety is taken seriously, then it is only *after* a crash that a plane becomes dangerous, as the hybrid material-regulatory reality that it represents collapses. It follows that the engineering work undertaken to recertify an aircraft after an accident is only partially a technical issue: it also represents a kind of normative redesign. That process of normative redesign works by absorbing the failure modes evident in the disaster – the violent destruction of the tyres and associated damage to the fuel tanks – and writing them back into regulatory frameworks that govern the design of the aircraft. The regulations, and as a result the aircraft, then come to perform those new modes of failure. Fitting new tyres to Concorde is therefore a way of repairing the norms governing commercial flight by means of engineering, allowing the type to operate *with the level of reliability expected of a civil jetliner*. With new tyres, Concorde performs that level of reliability, but it is also important that the safety it embodies is not really or purely a positive fact. As a machine, it performs a set of regulations that have absorbed a history of disaster (Downer 2007, 2017).

The key point here is how law is located in a complex technological system such as Concorde. Rules and regulations do not stand *apart* from or *over and above* the thing regulated. Rather, they seem to be *built into it*. Law forms a kind of ligature that binds the various components of the aircraft and their inherent uncertainties into a device that *performs* – something that works, carrying itself into the future, up to a point. Law anchors what it means to 'work' and the future realities in which that work will happen. It also defines the point at which the assemblage of the aircraft will lose its coherence and collapse, as well as providing the resources by which devices can be reconfigured and redefined, and can recover from disaster. It is in this sense that commercial flight is a total phenomenon comprising physical and social laws. From the perspective of aircraft, this, I suggest, is the ontological significance of law and regulation.

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Notes

1. The metal strip had dropped off the engine cowling of a Continental Airlines DC-10 that had departed previously. The strip had been poorly installed by Continental contractors and had worked loose. Continental Airlines and two named contractors were later prosecuted in France for their role in the accident. Continental was exonerated on appeal in 2012 (Associated Press 2012).

2. According to International Civil Aviation Organization definitions, accidents involve serious injury or loss of life, or severe damage to or destruction of aircraft or other property. Incidents are reportable events that are less serious than accidents (Strauch 2006).

3. Because my interest in this article is in the relationship between regulation and technology, I do not deal at length with the anthropology of documents (e.g. Carswell and Neve 2020; Hull 2012; Riles 2000; Street 2012), which would serve to foreground the BEA report itself, rather than the story it tells. An analysis of air accident reports *as documents* would be extremely interesting but represents a parallel project.

4. The performative aspect of these approaches marks their distinction from anthropology's home-grown 'ontological turn' (Henare et al. 2007; Holbraad and Pedersen 2017), which differs insofar as it imagines 'ontologies' as quasi-geometric (Holbraad 2020) systems of concepts that exist independent of practice. Anthropologists of the ontological turn, in opposition to Law (2002) and Mol (2002) especially, insist that 'realities' cannot be read off activities without reference to a system of 'concepts' that frame ontologies as realities (Viveiros de Castro 2013).

5. Strathern observes the analogy between this kind of organizing representation and anthropology. Anthropologists, she argues, have had an attachment to the idea of law because it is 'a descriptive activity which echoes [their] own descriptive endeavours' (Strathern 1985: 129).

6. Borrowing from Garfinkel's (1996) notion of 'instructed action', we might talk about 'regulated activity'.

7. For example, British Airways' engineering division offers 'Aircraft modifications including service bulletin and airworthiness directive embodiment' (British Airways n.d.).

8. Here it is worth remembering that the first passenger jetliner, the DH Comet, was very dangerous by the standards of contemporary jets (Owen 1998).

9. This creates a genuine problem for regulators faced with radically new designs or innovative uses of materials in aircraft whose safety and reliability must nevertheless be certified. Reason (1997: 171) calls this the 'regulator's unhappy lot' of being compelled to predict the behaviour of systems for which no precedent exists – and as a result, often being compelled to accept the assurances of the manufacturer to make a judgement. Part of the story of the progressive uprating of Concorde's tyres, discussed below, is a story of regulators refining their sense of what was safe for use with a hitherto untried kind of aircraft, a supersonic transport plane. Other examples of the problem include the design flaws of the De Havilland Comet (Owen 1998), the first fully pressurized airliner, and the more recent Boeing 787 (Federal Aviation Administration 2007), the first passenger aircraft to make extensive use of composite materials in its construction. The Comet proved, initially, to be extremely dangerous to operate despite being certified; the B787 required a number of special exceptions to Federal Regulations in order to be certified.

10. Another instance of referencing. One interesting aspect of the certification process, which I am not able to discuss at length here, is the way in which regulatory documents cite one another constantly, creating a web of intertextuality that in many ways mirrors the references that physical aircraft make to one another.

11. The report's conclusion (BEA 2002: 176) describes 'The ripping out of a large piece of tank in a complex process of transmission of the energy produced by the impact of a piece of tyre at another point on the tank, this transmission associating deformation of the tank skin and the movement of the fuel, with perhaps the contributory effect of other more minor shocks and/or a hydrodynamic pressure surge.' The speculative nature of this conclusion is clear.

12. This belt-and-braces approach was to a large extent political. Air France and Airbus favoured new tyres as a solution to the problems created by the Concorde crash, while British Airways and BAE Systems preferred armoured fuel tanks (Glancey 2015).

13. As well as being an object of pride for both French and British flag-carriers. It is worth noting that Concorde was never really economically viable. The development of the type was extremely expensive and had to be massively subsidized by both the French and British governments. Because very few jurisdictions were prepared to allow supersonic overflights of their territory, it could not operate supersonically across most of the world. It was mainly restricted to trans-Atlantic flights with periodic trips across the Arabian peninsular to Singapore. To make matters worse, Concorde entered service in 1976, immediately after the oil price shock of 1973–1974 when airlines were turning to wide-body transports like the Boeing 747, which offered vastly higher profit margins. Largely uneconomical, the twenty aircraft produced were sold to British Airways and Air France at significantly reduced rates (Chittum 2018; Glancey 2015).

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