The Challenger Space Shuttle Disaster: A Case Study in the Analysis of Binary Data Using Scatter Diagrams and Logit Regression[1]

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Abstract

On the morning of 28 January 1986 a U.S. Space Shuttle named "Challenger" exploded soon after take-off killing all seven crew members who were on board. The launch went ahead on a very cold morning despite attempts by a group of engineers to halt the launch arguing that it was unsafe to proceed given the likelihood of malfunctions occurring if the shuttle was launched when the temperature was below freezing. They failed to convince the decision makers involved that there was any strong connection between temperature at launch and the malfunction of a particular crucial part. In this paper we will see that if only the engineers had made proper use of scatter diagrams and/or logit regression they would likely have been able to make a convincing case to delay the launch of the shuttle.

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[1] I am grateful to Jenny Lye for helpful comments on an earlier version of the paper. I am also grateful to the Office of National Archives in Washington, DC for permission to reprint material from the 1986 Report of the Presidential Commission on the Space Shuttle Challenger Accident, Volume 1.

1. Introduction

The aim of this paper is to show you a very instructive example of the usefulness of Scatter Diagrams and of Logit Regression in decision making. The case study we will look at involves the Challenger Space Shuttle disaster.

I begin by summarising the circumstances in which on the morning of 28 January 1986 a U.S. Space Shuttle named "Challenger" exploded soon after take-off killing all seven crew members who were on board. The cause of the accident was found to be the failure of a rubber seal (called an "O-ring") which was in one of the Shuttle's rocket boosters. Evidence was given to an enquiry into the disaster that the O-rings were liable to malfunction in cold weather and that at the time of launch the temperature was below freezing. Now, it so happened that on the night before the Challenger was launched a large group of engineers and managers connected with the Shuttle program met for a number of hours to discuss the concerns that some of the engineers had about the consequences of the forecast record low temperatures for the ability of the O-rings to function properly. Although the engineers expressed their opposition to the launch, at the conclusion of the meeting the managers decided that the engineers had not made a convincing case that seal failure was related to temperature. Consequently, a decision was made to continue with the launch of the Shuttle with catastrophic results. It is widely thought that this was a mistake that would not have occurred had the engineers and managers collected and studied *all* relevant (and readily available) data and used sensible and simple statistical techniques to analyse it.

In this paper we will look at a scatter diagram relating temperature and seal damage for all Shuttle flights which took place before the Challenger launch - something the decision makers at the time did not do, although all of the data we shall use was available to them at the time. We will then apply Logit analysis to see if indeed it is the case that lower temperatures significantly increase the probability that a seal will malfunction (again, something the engineers and the decision makers failed to do). We will see that, had the NASA engineers or managers used Scatter Diagrams and/or Logit Regression, it would have been obvious to them that cold weather dramatically raised the probability of a disaster occurring. Indeed, we will see that, given the temperatures which prevailed at the time the Shuttle was launched, the probability of seal failure was close to 100%. Along the way I show you how to use the Logit regression coefficients to forecast the probability of an event occurring (in this case the failure of a rubber seal).

2. The Space Shuttle program

The US space shuttle was a reusable rocket-launched vehicle designed to go into Earth orbit, to transport people and cargo between Earth and orbiting spacecraft, and to then return to Earth, landing like a conventional airplane. It was developed by the National Aeronautics and Space Administration (NASA) of the United States. The first Shuttle was launched on April 12, 1981.

The Shuttle system consists of three major components: (i) a winged orbiter that carries the cargo and crew and contains the craft's computer and electronic hardware, as well as its three main engines; (ii) an external tank containing liquid hydrogen (fuel) and liquid oxygen (oxidizer) for the orbiter's three main rocket engines; and (iii) a pair of large, solid-propellant booster rockets. (See Figure 1.) During launch the Solid Rocket Boosters and the orbiter's main engines fire together, producing 31,000,000 newtons of thrust until roughly two minutes after lift-off, when the boosters burn out and are jettisoned by parachute into the ocean for retrieval, inspection and eventual reuse. After the orbiter has exhausted the propellants in the external tank, it is released from the shuttle and disintegrates while falling through the Earth's atmosphere.

[FIGURE 1 NEAR HERE]

The Shuttle program suffered a serious setback in 1986. On January 28 of that year the orbiter "Challenger" exploded 73 seconds after lift-off, killing its entire seven-member crew (including a high-school teacher, the first private citizen to fly aboard the craft). The accident occurred on the 25th Shuttle mission and resulted in the suspension of flights so that the reasons for the explosion could be investigated and the problem corrected. Shuttle flights were resumed in 1988 after corrective measures were satisfactorily completed and new safety systems installed in the three remaining orbiters/shuttles.[2]

3. The Challenger accident

As we have seen, the Booster Rockets are a key element in the operation of the shuttle. There is a Booster Rocket attached to each side of the external fuel tank. Without the boosters, the shuttle cannot produce enough thrust to overcome the earth's gravitational pull and achieve orbit.

A company named Morton Thiokol was awarded the contract to design and build the Solid Rocket Boosters. The booster is comprised of seven hollow metal

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[2] NASA was operating four Shuttles at the time of which Challenger was one. Prior to January 1986 there had been a total of 24 Shuttle launches of which 9 involved Challenger - the other 15 launches involved three other Shuttles which were named Columbia (7 launches), Discovery (6 launches) and Atlantis (2 launches). In 2003 Columbia's heat shield was damaged during launch with the result that the shuttle disintegrated as it re-entered the Earth's atmosphere, killing all of the crew on board.

cylinders. The solid rocket fuel is cast into the cylinders at the Thiokol plant in Utah, and the cylinders are assembled into pairs for transport to Kennedy Space Center in Florida. At Kennedy Space Center, the four booster segments are assembled into a completed booster rocket. (See Figure 2.) The joints where the segments are joined together at Kennedy Space Center are known as 'field joints'.[3] Each joint is sealed by flexible rubber rings called 'O-rings'. At this point one needs to understand exactly what role the O-rings play in the Solid Rocket Booster joints. When the material in the Rocket Booster starts to heat up, it expands and pushes against the sides of the Booster. At the same time the metal which forms the booster itself will be expanding and so the rubber seals need to also expand in order to ensure that the joint remains sealed and no gas can escape. If there is an opening in a joint in the Booster (perhaps because the rubber O-rings have not expanded at the same rate as the metal casing and so the joint will not remain completely sealed), the hot gas will escape through that opening with possibly catastrophic results.

Being made of rubber the O-rings become rigid in temperatures below freezing and cannot expand to fill any gaps between the segments that make up the booster. This means that if a launch occurs in freezing conditions, it is possible for the gas to find gaps in the joints. It was this which happened on Challenger. The exact sequence of events went like this: At the time Challenger took off (11:38 AM on Tuesday January 28), the temperature of the field joint on the right-hand booster was about 28^{o} Fahrenheit (F).[4] As a result the O-ring was too cold to seat properly and gases at over 5000^{o}F burned past the O-rings. Within seconds, flames from the field joint burned through to the outside of the External Tank, used to supply highly flammable liquid hydrogen and liquid oxygen fuel to the shuttle's engines during the launch. The flame eventually burned through the metal skin of the tank and straight onto a large amount of liquid hydrogen and oxygen which was inside. A massive explosion then occurred, tearing the shuttle apart.

[FIGURE 2 NEAR HERE]

Immediately after the accident a Presidential Commission of Enquiry was established. Given what I have said above it is not surprising that they concluded that: "The loss of the Space Shuttle Challenger was caused by a failure in the joint between the two lower segments of the right Solid Rocket Motor. The specific

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[3] This is because they allow the rocket booster to be assembled "in the field" rather than at the plant where they were manufactured.

[4] In the Fahrenheit system 32 degrees is equivalent to zero degrees Centigrade. In other words, at 32^{o}F water freezes. So a temperature of 28 degrees F is "below freezing" (i.e. it is below 0 degrees Celsius).

failure was the destruction of the seals that are intended to prevent hot gases from leaking through the joint during the propellant burn of the rocket motor" (Report of the Presidential Commission on the Space Shuttle Challenger Accident, 1986, p 40). The seal failed because of the extreme cold temperatures prevailing prior to, and at, the time of the launch. "Simply stated, cold temperatures made the synthetic rubber O-rings less elastic, and they took longer to spring into their proper grooves and seal the joint" (McConnell, 1987, p 183). As a result of the failure of the seal to work properly an explosion occurred which destroyed the Shuttle, killing its crew.

During the course of its hearings, the Commission of Enquiry discovered that the night before the Challenger was launched, a large group of engineers and managers connected with the Shuttle program met to discuss the concerns that some of the engineers had about the consequences of the forecast record low temperatures for the ability of the O-rings to function properly. The Commission also discovered that, although this meeting went for some 4 hours and although the engineers at Thiokol were opposed to the launch, at the conclusion of the meeting the Thiokol (and NASA) managers decided that there was no evidence that seal failure was related to temperature. Consequently, they decided to proceed with the launch the following morning. The rest, as they say, is history.

What follows is an attempt to bring together various things which have been written about that meeting and to bring out the lessons to be learned about the importance of analysing data with the aid of Scatter Diagrams and especially of analysing binary data with the aid of Logit Regression. Commentators seem to agree that had the engineers and managers used appropriate data analysis tools, they would surely have called off the launch and waited for the temperature to rise to a safe level. As the Presidential Commission noted: "A careful analysis of the flight history of O-ring performance would have revealed the correlation of O-ring damage and low temperature. *Neither NASA nor Thiokol carried out such an analysis*; consequently, they were unprepared to properly evaluate the risks of launching the Challenger mission in conditions more extreme than they had encountered before" (Report of the Presidential Commission on the Space Shuttle Challenger Accident, 1986, p 148).

4. To launch or not to launch?

Challenger was originally scheduled to lift-off on Thursday 23rd of January. However, a number of factors contributed to the launch being postponed twice until the following Tuesday, January 28th. The first delay was because a weather front was expected to move into the area, bringing rain.[5] The second launch delay was caused by a defective switch in the hatch locking mechanism and by problems in replacing the hatch handle. By the time these problems had been sorted out, the weather front had started moving again, and was bringing with it record-setting low temperatures to the Florida area.

[FIGURE 3 NEAR HERE]

Late in the afternoon of Monday 27 January (the day before Challenger was now scheduled to take-off), engineers at Morton-Thiokol in Utah (the manufacturers of the Solid Rocket Boosters) became alarmed when they heard that temperatures for launch were predicted to be below freezing. They contacted Thiokol managers and NASA officials and expressed their view that the Rocket Booster seals would not function properly at such low temperatures and put in writing their view that the Shuttle should not be launched until the temperature reached 53^{o}F. NASA officials decided to hold a teleconference that evening (the evening before the re-scheduled launch day) in order to discuss the concerns about the low temperature performance of the boosters. This teleconference was held between engineers and management from Kennedy Space Center at Cape Canaveral in Florida (the section of NASA responsible for the final assembly of the Boosters and for conducting shuttle launches), Marshall Space Flight Center in Alabama (the section of NASA responsible for procuring and exercising quality control over components of the shuttle system including the Solid Rocket Boosters) and Morton-Thiokol (the company which manufactured the Boosters).[6] Thiokol's engineers gave an hour-long presentation,[7] arguing that the cold weather (the temperature of the field joints in the booster were predicted to be at 29^{o}F. at the time of launch) would lead to O-ring failure. Amongst other things, they pointed out that the lowest temperature experienced by the O-rings in any previous mission was 53^{o}F, the January 24, 1985 flight and that the seals in the Boosters used on that flight were found to be damaged. NASA staff and Thiokol managers responded by pointing out that the data on damage in relation to temperature at launch presented by the Thiokol engineers showed that damage had also occurred at a launch which took

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[5] Rain during take-off was a problem because it had the propensity to damage and even dislodge the heat-resistant tiles on the outside of the orbiter. This would make re-entry into the earth's atmosphere extremely dangerous.

[6] In all, thirty-four engineers and managers participated in the teleconference (Vaughan, 1996, p 292).

[7] Copies of all of the faxes containing tables of data etc presented during the teleconference can be found in Vaughan, 1996, pp 293-9.

place on 30 October 1985 when the temperature was 75^{o}F. It was also asserted that, since the engineers had no temperature data below 53^{o}F, they could not prove that it was unsafe to launch at temperatures below that level(!). Engineers at Thiokol tried to convince their senior managers to recommend to NASA that they not proceed with the launch but their managers kept insisting that the data presented to them showed no correlation between temperature and the damage to the O-rings in previous missions. NASA staff from the Marshall Fight Centre also commented that the data was inconclusive and challenged the engineers' logic.

Following a lengthy discussion by the Thiokol managers (without the engineers being present) a recommendation was faxed to NASA by the senior manager at Thiokol. The fax stated that the cold was still a safety concern, but Thiokol management had found that the original data was indeed inconclusive and their "engineering assessment" was that launch was recommended.[8] NASA managers then decided to go ahead with the launch (despite the fact that the predicted launch temperature was outside of their own operational specifications!). "The men from NASA wanted their launch to proceed on schedule and would listen to no reasonable argument that recommended delay. The Thiokol managers overruled their engineering experts to satisfy a demanding customer" (McConnell, 1987, p203). The Presidential Commission found that "Thiokol management … recommended the launch of the Challenger at the urging of NASA and contrary to the views of its engineers in order to accommodate a major customer" (Report of the Presidential Commission on the Space Shuttle Challenger Accident, 1986, p 104). However, it is also true that the Thiokol engineers failed to convince their own management that there was a clear connection between launch temperature and seal damage/failure.

5. The failure to collect, present and properly analyse all available and relevant data

Why were the engineers at Thiokol unable to convince their senior managers to recommend to NASA that they not proceed with the launch? During the discussion between the engineers and managers attention focussed (only) on the temperatures at which O-rings had been damaged in previous flights.[9] It is important to notice that this data refers only to flights where damage had occurred

[8] They stated this even though their own engineers had no part in writing the new recommendation and refused to sign it.

[9] Excellent accounts of the discussion are to be found in Tufte (Tufte, 1997, pp 39-53), Vaughan (1996) and Lighthall (1991). What commentators called "damage" to the seals the Presidential Commission used the term "O-ring thermal distress".

and did not include information of the temperature which prevailed at the time of launching of the seventeen flights during which no damage occurred. For the cases they did discuss, seal damage was observed both at the high end (75 degrees Fahrenheit) and at the low end (53 degrees Fahrenheit). No one who took part in the meeting asked for, or made reference to, temperature data on flights where no damage occurred in addition to the data for flights where damage occurred. As one commentator has put it: "Analysis of the Tables of data and arguments faxed to all participants by Thiokol... reveal an absence of elementary statistical ideas and analytical methods - ideas and methods critically relevant to the focal argument that temperature was, or was not, a significant cause of the O-ring damage" (Lighthall, 1991, p 65).[10]

The failure to collect, present and properly analyse all relevant data[11] has been put in its starkest form by Edward Tufte (a graphic designs expert, statistician and Yale professor[12]). In his fascinating book titled *Visual Explanations*, he presents a thoroughly documented and damning criticism of the people involved in the Challenger launch decision. He writes: "For hours (from 8.15pm to 12 midnight) the rocket engineers and managers considered the question: Will the rubber O-rings fail catastrophically tomorrow because of bad weather? These discussions concluded at midnight with the decision to go ahead. That morning Challenger exploded 73 seconds after its rockets were ignited". "Had the correct scatterplot or data table been constructed no one would have dared to risk the Challenger in such cold weather" (Tufte, 1997, p 39 & 52).

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[10] As we shall see, "Simple analysis of variation and co-variation show not only that such analyses were possible but also that they would have quantified a strong, negative relationship between the two variables whose relationship was not quantified and in the end was doubted and discounted" (Lighthall, 1991, p 73).

[11] We have already seen that one of the findings of the Presidential Commission was that: "A careful analysis of the flight history of O-ring performance would have revealed the correlation of O-ring damage and low temperature. Neither NASA nor Thiokol carried out such an analysis; consequently, they were unprepared to properly evaluate the risks of launching the Challenger mission in conditions more extreme than they had encountered before." (Report of the Presidential Commission on the Space Shuttle Challenger Accident, 1986, p 148.)

[12] In Tufte's profound ethos of information design, "clear and precise seeing becomes as one with clear and precise thinking" (Tufte, 1997, p 530). I especially commend to the reader his three books on the presentation of information in visual form which are listed in the bibliography.

6. Scatter Diagrams can aid decision making

One very useful way to graphically convey in formation about a relationship between two variables, such as temperature and damage - a schema learned in any introductory course in statistics - is to use a scatter diagram. Such a diagram would cast one variable, say temperature, on the horizontal axis and the other, some index of O-ring damage, on the vertical axis, and would place one dot in that two-dimensional space for each of the launches to date. An alternative would be to present a Table listing all the pairs of temperature and damage readings in order, say from low to high temperature, showing how as temperature rose, numbers representing O-ring damage decreased. Neither of these types of displays were presented during the teleconference on the night before the launch. The Tables and Diagrams they presented in the teleconference "were essentially irrelevant to the question that the engineers were attempting to answer" (Lighthall, 1991, p 72f).

Data presented during the teleconference did not include any scatter diagrams or any statistical analysis of the past history of O-ring damage due to temperature. As we have seen, the focus of the discussion between the engineers and the managers at Thiokol was on only those flights where damage had resulted. For future reference note that we can represent the information the engineers provided to their managers in the form of a graph with temperature at launch on the horizontal axis and with damage indicated by recording a value of 1 on the vertical axis. See Figure 4.

[FIGURE 4 NEAR HERE]

Looking at this graph it is understandable that the managers at Thiokol were not convinced that there was any clear relationship between seal damage and temperature.

However, if a scatter diagram (or Table) containing data for *all* previous launches had been drawn up and presented to the meeting everyone involved would have observed that damage occurred for only three of the nineteen flights in which the launch temperature was above 65 degrees Fahrenheit compared with damage for all four flights with a launch temperature below 65 degrees Fahrenheit (see Figure 5). Surprising as it may seem to us, no one involved examined the data using a scatter diagram as presented in Figure 4. Had they done so they would have realised that the flights with no damage all correspond to relatively warm launch temperatures and it is apparent that most of the flights where some damage correspond to relatively cool launch temperatures. A key lesson for us is not only that scatter diagrams are useful but the need to incorporate *all* relevant information in the scatter diagram.

[FIGURE 5 NEAR HERE]

While it is correct to say (as Lighthall (1991) and Tufte (1997) do) that scatter diagrams would have aided the analysis during the teleconference there is a far more relevant and powerful tool which ought to have been used to analyse the problem. The obvious statistical technique to use is Logit regression. One reason for this is because they key issue was binary one - would the seals fail or would they not? A second reason is that the launch or not launch decision would have to be made on the balance of the probabilities. Logit regression is the best tool for handling these issues.

7. Logit Regression

In the case of a regression where the dependent variable (Y) is a dummy or'binary' variable (in our case the dependent variable adopts a value of 0 or 1), we can interpret the equation as estimating the probability that Y = 1 (often written as $P_{y=1}$ or just P alone). How do we know this?

The expected value of any random variable will be the sum of the values which can be adopted by that variable each multiplied by the probability that that value will be observed. In the case we are interested in the variable may only adopt a value of 1 or 0. So the expected value of the variable will be the sum of the probability that the variable will adopt the value of 1 multiplied by 1 plus the probability that the variable will adopt the value of 0 multiplied by 0. Now obviously if we multiply the probability that the variable will adopt the value of 0 by 0 the result will be a value of zero. It follows that the expected value of the variable will simply be the probability that the variable will adopt the value of 1 multiplied by 1. In what follows we will denote this by the symbol $P_{y=1}$.

In a logit model we assume that $P_{y=1}$ is a non-linear function of one or more explanatory variables and that the particular non-linear function takes the form of a Logistic equation. In the case of one explanatory variable (X) the model for $P_{y=1}$ takes the following form:[13]

$$E(Y) = P_{y=1} = 1/(1 + EXP\text{-}(\alpha + \beta X))$$

Notice two things. First, the relationship between $P_{y=1}$ and X depends crucially upon the value of β. If β is positive the probability that Y = 1 (ie $P_{y=1}$) will rise as X rises whereas if β is negative the probability that Y = 1 (ie $P_{y=1}$) will fall as X rises. Second,

[13] Notice that this equation may be transformed to yield the following expression: $LN(P_{y=1}/(1 - P_{y=1})) = \alpha + \beta x$.

we note that it is a feature of the Logistic equation set out above that $P_{y=1}$ must always lie in the range 0 – 1.

7.1 Logit Regression can aid decision making

The dependent variable in a Logit regression is a binary (dummy) variable. In the case we are considering it would have a value of 1 if one or more of the seals experienced damage during launch and 0 if none of the seals experienced damage. The obvious explanatory variable for us to use is Temperature at the time of launch - by this is meant the temperature of the Booster Rocket joints at launch measured in degrees Fahrenheit. Data on temperature and damage is available for all 24 flights which took place prior to the Challenger launch.[14] Table 1 gives you the data. I have arranged it in order from lowest temperature to highest. Notice that we are not using any data which was not available to engineers, managers and NASA officials at the time they met to consider whether or not to go ahead with the Challenger launch.

[TABLE 1 NEAR HERE]

I report below the key results in relation to the coefficients obtained by fitting a Logit model to the data reported in Table 1.

Coefficient Standard Error p-value

Constant 15.297 7.328 0.037

Temperature -0.236 0.107 0.028

7.2 The probability of failure

The fact that in Logit/Logistic regression we can interpret the equation as estimating the probability that Y = 1, means that when we look at the significance and sign of the coefficient on the explanatory variable (Temperature) we are examining the effect it has on the likelihood or the probability that a seal will fail to function properly.

[14] The data is taken from the Report of the Presidential Commission on the Space Shuttle Challenger Accident, 1986, p 146.

The key issues to be considered are: (a) Is the probability of failure related to temperature? (b) If so, is it negatively related to temperature? (c) What was the probability of failure given the temperatures which: (i) were assumed would prevail at the time of the launch (29^{o}F), (ii) which actually prevailed at the time of launch (28^{o}F) and (iii) the engineers themselves had argued was safe (53^{o}F)? We will deal with each in turn.

(a) Is the probability of failure related to temperature and, if so, is it negatively related to temperature? The slope coefficient on the explanatory variable Temperature is negative, indicating that the higher the temperature, the lower is the probability of failure (and vice-versa, the lower is the temperature, the higher is the probability of failure).[15] Looking at the p-values we can say that the coefficient is significantly different from zero and that it is significantly less than zero, both at the 5% level.

(b) What was the probability of failure given the temperatures which were(i) forecast for the launch and (ii) which actually prevailed at the time of launch? We can use the Logistic equation to make forecasts of the probability of failure given Temperature at launch. Given the coefficients in the Logit equation, the implied equation relating $P_{Y=1}$ to Temperature is:

$$E(Y) = P_{y=1} = 1/(1 + EXP\text{-}(15.297 – 0.236*Temperature))$$

We can use this equation to predict the Probability of seal damage for various temperatures. Figure 6 shows the predicted values of $P_{Y=1}$ for Temperatures in the range 20 - 90 degrees Fahrenheit.

[FIGURE 6 NEAR HERE]

[15] The slope coefficients in a Logit are a measure of the effect of a unit change in X on the Logarithm of the Odds Ratio - i.e. on the logarithm of ($P_{y=1}$/(1 - $P_{y=1}$)). (See note 13 above.) However, the sign and significance of the effect of a unit change in X on the logarithm of ($P_{y=1}$/(1 - $P_{y=1}$)) and on $P_{y=1}$ will be the same. If the slope coefficient is negative (as it is in this case), an increase in Temperature leads to a decrease in the logarithm of ($P_{y=1}$/(1 - $P_{y=1}$)). If an increase in to is resulting in a decrease in the logarithm of ($P_{y=1}$/(1 - $P_{y=1}$)), it must be because the increase in Temperature is making $P_{y=1}$ decrease. All of which is to say that if Temperature is having a significant negative effect on the logarithm of ($P_{y=1}$/(1 - $P_{y=1}$)) then it must also be having a significant and negative effect on $P_{y=1}$.

In this particular context it is instructive (and fair to the participants in the teleconference) to make three predictions. First what is the probability that a seal will fail given the predicted temperature before the launch took place? Second, what is the probability that a seal will fail given the temperature which actually prevailed at the time of the launch? Third, what is the probability that a seal will fail given the temperature which the engineers themselves regarded as safe for launch? We will look at each in turn although we will see that they give us essentially the same answer, the probability of failure in each case is above 90%.

What temperature were the engineers assuming when they made their recommendation? We are told that before their evening teleconference "the data they were working on assumed a temperature of 26^{o}F. for the scheduled launch time of 9:38 Tuesday morning. With a predicted ambient temperature of 26^{o}F at launch, the O-rings were estimated to be at 29^{o}F." (McConnell, 1987, p 194f). Using the Logistic coefficients reported above we find that for a temperature of 29 degrees Fahrenheit, the Probability that a seal will fail is (ie the predicted value of $P_{y=1}$ is) 0.9998 or 99.98%. For all intents and purposes this is a probability of 1 or 100%.

You will recall that the final communication from the managers at Thiokol at the end of the teleconference was a recommendation to launch. The faxed message which contained this recommendation stated that, in giving their assessment, they anticipated that the temperature on the Solid Rocket Boosters in the vicinity of the O-rings "would be 20 degrees[16] colder than ever before (i.e. 20 degrees colder than 53 degrees F)".[17] In other words, they were working on the assumption that the temperature would be 33^{o}F. at the time of launch (McConnell, 1987, p 200 and Vaughan, 1996, p 299). Using the Logistic coefficients reported above we find that for a temperature equal to 33 degrees, the probability that a seal will fail (ie that $P_{y=1}$) is 0.9994 or 99.94%. Again, for all intents and purposes this is a probability of 1 or 100%.

As it turned out, "the actual ambient temperature at time of launch was 36 degrees Fahrenheit and the temperature of the Solid Rocket Booster surface at the position

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[16] It would seem they were working on the assumption that the take-off would be delayed until later in the morning and that the temperature would be 33^{o}F at the time of launch (McConnell, 1986, p 200).

[17] The lowest temperature experienced by the O-rings in any previous mission was 53^{o}F, the January 24, 1985 flight (the seals were damaged on that flight - it is this which more than anything else was worrying the engineers at Thiokol.)

where the seal broke was estimated to be 28 degrees Fahrenheit" (Report of the Presidential Commission on the Space Shuttle Challenger Accident, 1986, p 70). Using the coefficients reported above we find that for a temperature equal to 28 degrees, the Probability that a seal will fail (ie that $P_{y=1}$) is 0.9998 or 99.98%. Once again, for all intents and purposes this is a probability of 1 or 100%.

Finally, we consider the engineers view that it was safe to launch if the temperature was equal to or greater than 53^{o}F. Using the coefficients reported above we find that for a temperature equal to 53^{o}F, the Probability that a seal will fail (ie that $P_{y=1}$) is 0.9397 or 93.97%. A probability of failure above 90%, and this for the temperature the engineers (widely regarded as the heroes whose advice ought to have been accepted) stated was "safe". Indeed, it is worth noting that, given our estimated equation, the temperature has to be above 65^{o}F for the probability of damage to fall below 50%.

All of our findings are in marked contrast to that provided the evening before the launch by the engineers and project managers "whose 'analysis' of the O-ring performance and temperature data, which focussed on examining the cases where damage had occurred, found no evidence that a relationship existed between these two factors" (Pinkus, p 318). In doing so, "they missed an opportunity to see the true pattern in the data. The engineers uniformly noted that they could not prove that a relationship existed between O-ring failure and temperature, even though they did not statistically analyse the data in order to ascertain if a relationship did exist" (Pinkus, p 318f).

I put it to you that Logit regression is a powerful tool in this context as it would be in any situation where the nature of the decision variable can be conveniently treated as a binary variable.

8. Lessons

1. It is important to carry out proper statistical[18] data analysis, taking into account *all* information appropriate to the problem being studied.

2. Logit analysis is an appropriate tool to use in many 'decision circumstances'. In this case it provided a clear answer to the problem at hand. It was very likely to be unsafe to launch the shuttle in the weather conditions at the time.

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[18] Statistical analysis is necessary because we must recognise that there will be measurement error and other influences which create 'noise'.

3. Tufte and others are correct to say that the use of Scatter Diagrams may have aided the analysis and so might have led to the 'right' decision being made. As Tufte himself has often pointed out, we should be aware that: "If displays of data are to be truthful and revealing, then the logic of the display design must reflect the logic of the analysis. Visual representations of evidence should be governed by principles of reasoning about quantitative evidence. For information displays, design reasoning must correspond to scientific reasoning. *Clear and precise seeing becomes as one with clear and precise thinking.*" The relevant principles both for reasoning about statistical evidence and for the design of statistical graphics imply that we should: "1. Document the sources and characteristics of the data, 2. Insist on appropriate comparisons, 3. Demonstrate mechanisms of cause and effect, 4. Express those mechanisms quantitatively, 5. Recognise the inherent multi-variate nature of analytic problems and 6. Inspect and evaluate alternative outcomes. It also helps to have an endless commitment to finding, telling and showing the truth" (Tufte, 1997, p 53).

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Figure 1: The Space Shuttle with its External Fuel Tank (1) and the Solid Rocket Boosters (2). Source: US Presidential Commission Report, 1986, p 3.

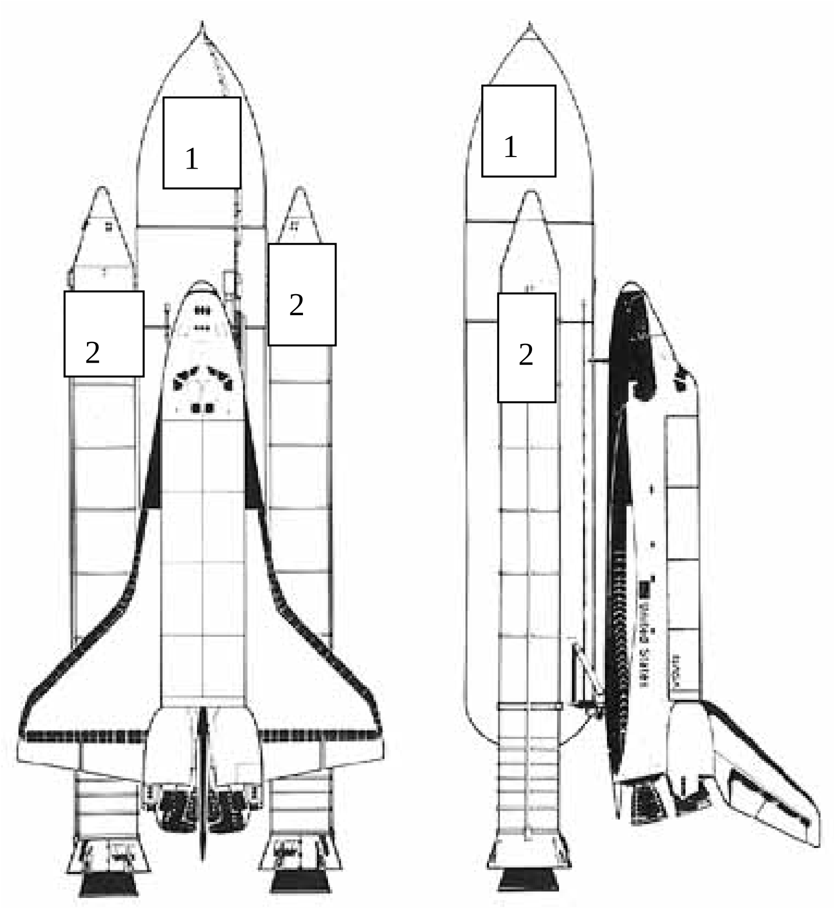


Figure 2: A Solid Rocket Booster and its segments. Large seals called O-rings (rubber rings about 4 metres in diameter) would be placed around the circumference of each section where they are joined together. The arrow shows the position of the seal which failed on the Booster on Challenger's Right-Hand Side. Source: US Presidential Commission Report, 1986, p 52.

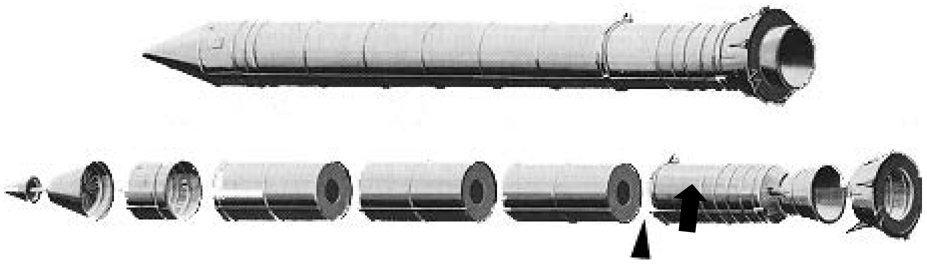


Figure 3: The Space Shuttle Challenger on the launch pad in the early morning of launch day. Source: US Presidential Commission Report, 1986, p 112.

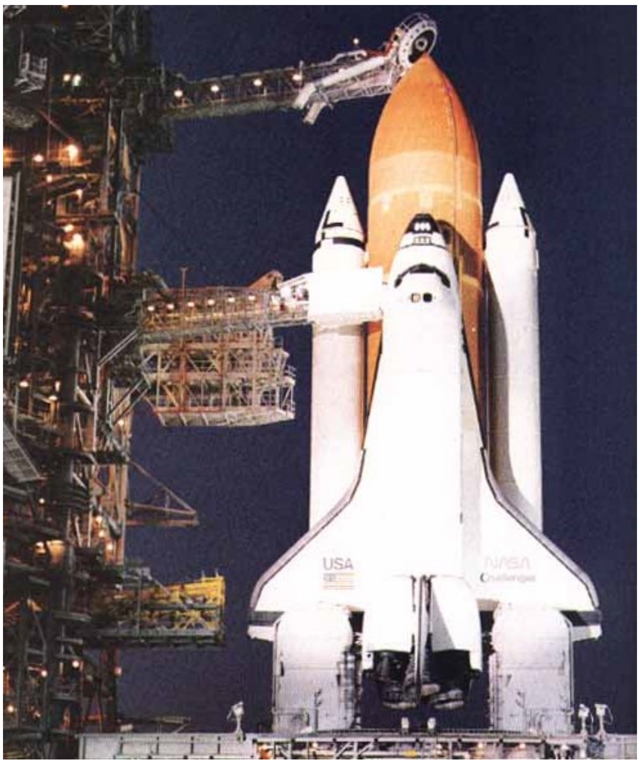


Figure 4: Launch temperature (on the horizontal axis) for flights where seals were found to be damaged (a value of 1 indicates damage occurred)

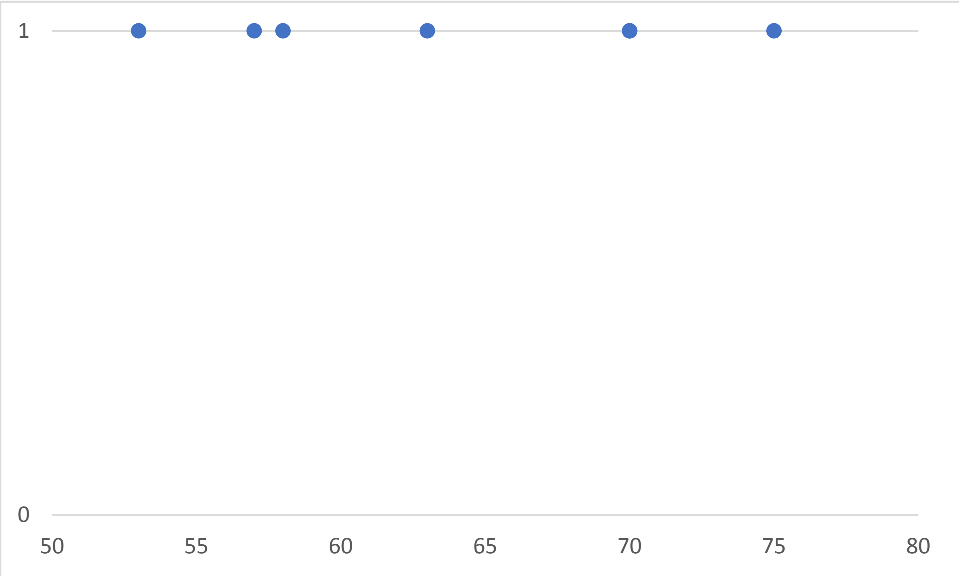
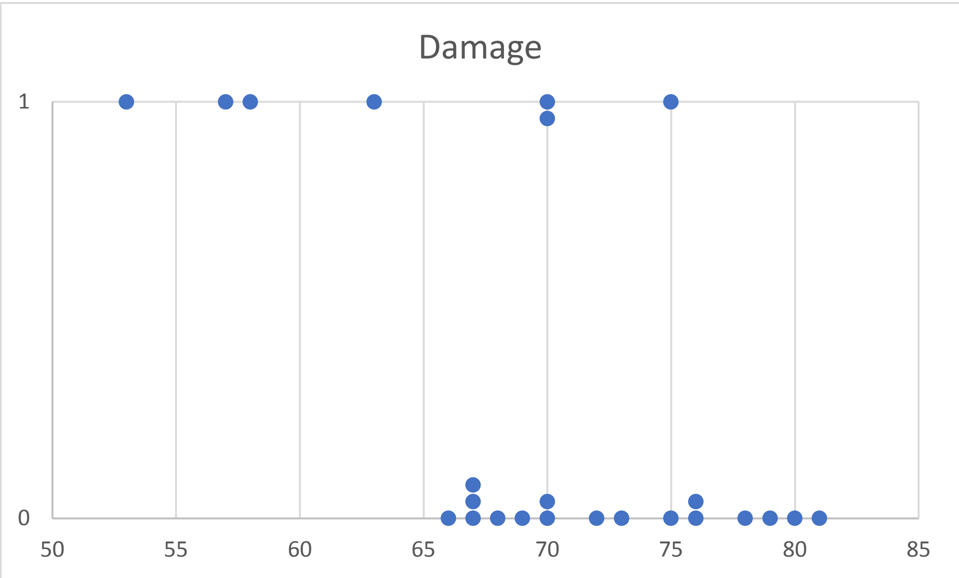


Figure 5: Graph of Damage to Seals[19] (Y = 1 or N = 0, vertical axis) against Temperature (horizontal axis). Source: Report of the Presidential Commission on the Space Shuttle Challenger Accident, 1986, p 146.



[19] Note that where there are more than one '0' recorded for any temperature in Table 1 I have 'stacked' the dots above each other but in each case you should regard them all as having a value of 0.

Figure 6: How the estimated value of $P_{y=1}$ varies with temperature

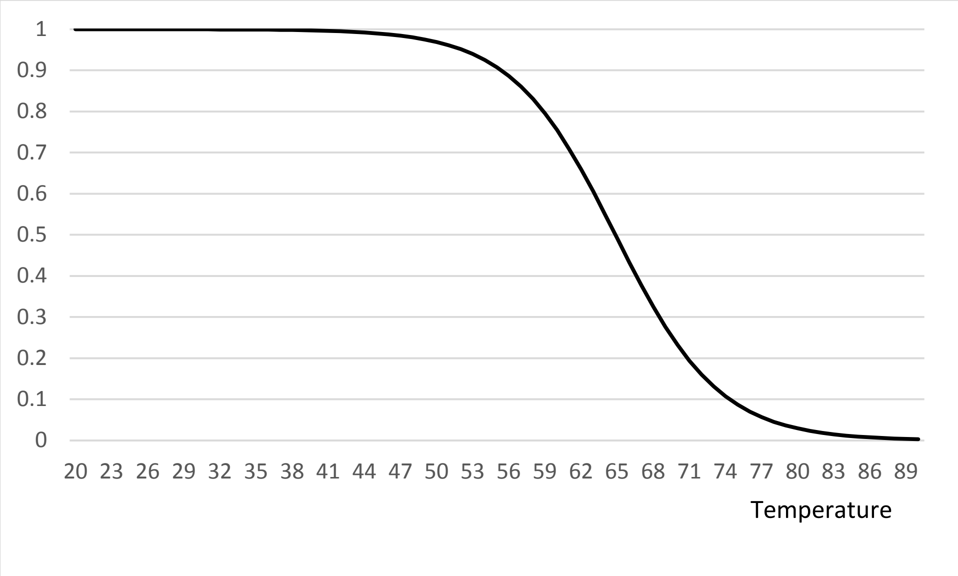


Table 1: Temperatures of joints on all previous flights with 1 indicating that damage to one or more seals had occurred and 0 indicating that no damage occurred. Source: Report of the Presidential Commission on the Space Shuttle Challenger Accident, 1986 p 146.

Temperature (^{o}F)	Damage occurred (Y = 1, N = 0)
53	1
57	1
58	1
63	1
66	0
67	0
67	0
67	0

68	0
69	0
70	0
70	0
70	1
70	1
72	0
73	0
75	0
75	1
76	0
76	0
78	0
79	0
80	0
81	0