1 Introduction

Traffic safety – a grossly underemphasized problem

More than a million people are killed on the world's roads each year.[1] The total is expected to increase steeply as the number of motor vehicles increases rapidly in many formerly less-motorized countries, and will likely exceed 2 million by the year 2020. Traffic crashes are one of the world's largest public health problems. The problem is all the more acute because the victims are overwhelmingly young and healthy prior to their crashes.

More than 40,000 people are killed on the roads of the United States each year.[2,3] In a typical month more Americans die in traffic than were killed by the 11 September 2001 terrorist attacks on New York and Washington. The families of the traffic-crash victims receive no particular consideration or compensation from the nation or its major charitable organizations. Since the coming of the automobile in the early days of the twentieth century, more than three million Americans have been killed in traffic crashes,[4] vastly more than the 650,000 American battle deaths in all wars, from the start of the revolutionary war in 1775 through the 2003 war in Iraq.[5]

When 14 teenagers died in the 1999 Columbine High School shootings,[6] much of the population of the US, led by President Clinton, grieved along with the bereaved families. Yet more teenagers are killed on a typical day in US traffic. In 2002, 5,933 people aged 13-19 were killed, which is an average of 16.3 teenagers killed per day.[7] These deaths barely touch the nation's consciousness. Families bereaved by a traffic death are no less devastated than the Columbine families. Indeed, their burden may be even more unbearable as they do not receive the support provided to the Columbine families.

Injuries due to traffic crashes vastly outnumber fatalities, with over 5 million occurring per year in the US, most of them minor.[8] The number of injuries reported depends strongly on the level of injury included. Applying the US ratio of 120 injuries for each fatality implies about 120 million annual traffic injuries worldwide. Dividing this by the world population of 6 billion,[9] implies that the average human being has a near two percent chance of being injured in traffic each year – more than a fifty percent chance in a lifetime.

Traffic crashes also damage property, especially vehicles. By converting all losses to monetary values, it is estimated that US traffic crashes in 2000 cost $231 billion,[8] an amount greater than the Gross Domestic Product of all but a few countries.

This book describes what has been learned by applying the methods of science to understand better the origin and nature of the enormous human and economic losses associated with traffic crashes. Particular attention is devoted to describing successful and unsuccessful interventions. Information from throughout the world is used, although more from the US than from any other country. This is mainly because, with 226 million vehicles in 2002,[3] the US provides more data than any other single nation. In addition, the US Department of Transportation maintains data files of unmatched magnitude, availability, and quality.[10]

In view of the enormity of the losses in traffic, it is not surprising that different facets of the problem are illuminated by many disciplines. Guidance is sought from basic physical principles, engineering, medicine, psychology, behavioral science, law, mathematics, logic, and philosophy. Phenomena that flow in a fairly direct way from the properties of mechanical systems and the human body are expected to apply in general and not just to the laboratory or jurisdiction in which they were measured. We assume this to be so, notwithstanding the closing remarks of an attorney to a New Jersey jury, "The laws of physics are obeyed in the laboratory, but not in rural New Jersey."[11] The jury, evidently moved by the force of this argument, found in favor of his client!

There is no reason why the effectiveness of occupant protection devices such as safety belts or airbags in preventing fatalities should vary all that much from jurisdiction to jurisdiction. For the same wearing rates, safety belts are expected to produce a similar percent reduction in fatalities in New Jersey as anywhere else. However, because no single state provides sufficient data to estimate belt effectiveness satisfactorily, such estimates are better based on data from the entire nation. On the other hand, many aspects of traffic safety are highly jurisdiction-specific due to variations in cultural or legal traditions. For example, alcohol plays different roles in traffic safety in Sweden, Saudi Arabia, the US, and Israel.

While safety is an important consideration in many human activities, it has a particularly prominent role in transportation. Every type of transportation system involves some risk of harm, as has been the case since antiquity, and seems likely to remain so in the future. The primary goal of transportation, the effective movement of people and goods, is better served by ever increasing speeds. A substantial proportion of technological innovation for the last few thousand years has focused on increasing transportation speeds, from human and animal muscle power to supersonic flight.

The subject of this book is crashes of vehicles running on wheels propelled by engines along public roads. The term *traffic* will refer to this system unless stated otherwise. Many concepts that pervade traffic safety and apply to vehicle crashes in general can be illustrated using the example of the most famous transportation crash of all time – one which did not occur on a road.

The sinking of the *Titanic*

On Sunday 14 April 1912, the 47,000-ton liner *Titanic* maintained its top speed of 22.5 knots (42 km/h) despite receiving nine ice warnings. At 11:40 pm the crew reported an iceberg directly ahead. Despite evasive action, a glancing impact ripped a 90 meter gash in the starboard side. The *Titanic* sank at 2:20 am on Monday 15 April, 2 hours and 40 minutes after the impact, with the loss of over 1,500 lives, including that of the 62-year-old captain, Edward J. Smith.[12]

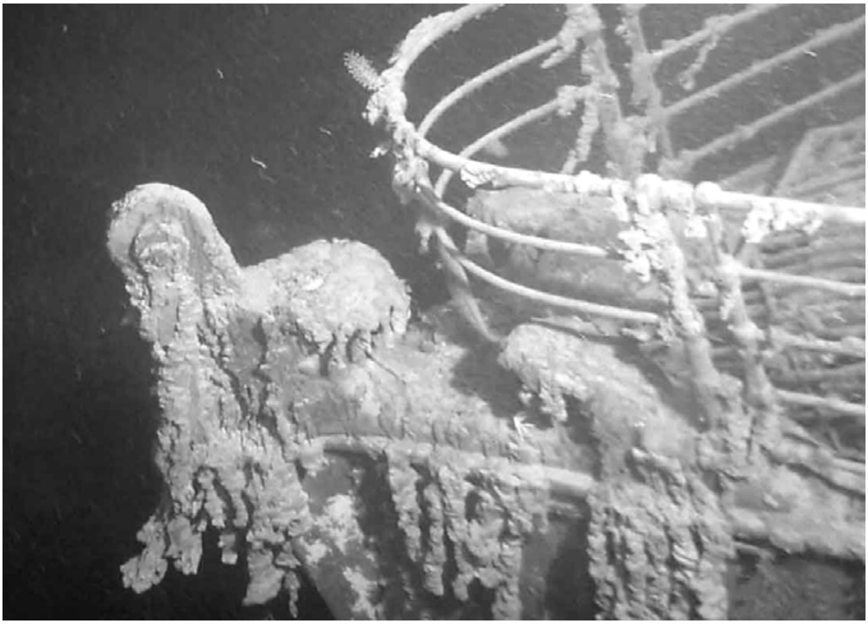

Figure 1-1. Bow of the *Titanic*, 3.8 km under the Atlantic Ocean. Photographed 2 September 2000 by Leonard Evans.

What if?

Any incident leading to harm begs a series of agonizing “what if” questions. What if, by chance, the *Titanic* had been a few dozen meters north or south of its actual position? What if the lookout had spotted the iceberg a few seconds earlier? What if there had been more effective procedures for deploying the available lifeboats? What if there had been more lifeboats? If the available lifeboats had been safely filled well beyond their stated heavy-sea capacity, could everyone have been saved? It is generally concluded that if the ship had maintained its initial high speed, the resulting increase in rudder effectiveness would have prevented contact with the iceberg. It is also claimed that cutting the speed to half, rather than stopping completely after impact, forced additional water into the vessel. Another hour afloat could have had a substantial effect on casualties, as the liner *Carpathia* arrived less than two hours after the *Titanic* sank.

What if the captain had been younger? The *Titanic's* skipper, 62-year-old Captain Edward J. Smith, senior captain of the White Star Line, was on his last scheduled voyage.[12] In finest maritime tradition, he went down with his ship. Notwithstanding all the advances in gerontology, medicine, monitoring, and anti age-discrimination legislation, present US law prohibits anyone of Captain Smith's age from piloting a passenger-carrying aircraft. Captain Smith's behavior, before and after the crash (well portrayed in Cameron's movie *Titanic*),[13] was likely markedly different from what it would have been when he was in his 40s. This raises the question "Was the sinking of the *Titanic* an older driver problem?"

What if impact had been head-on? One "what if" given less attention than others is: What if no one had spotted the iceberg and the *Titanic* had crashed head-on into it at 42 km/h? When a car traveling at 42 km/h strikes an immovable barrier, about 8% of its total length (or about 0.4 m) is crushed.[14] The uncrushed portion of the car experiences an average deceleration of 170 m/s^2, equivalent to 17 times the acceleration due to gravity, or 17 G. The associated forces of the occupants against their safety belts are likely to produce some injuries (unbelted occupants would sustain greater levels of injury as they continue to travel at 42 km until abruptly stopped by striking the near-stationary interior of the vehicle). Assume, as a very rough approximation, that 8% of the *Titanic*'s 269 m length would have been crushed by the head-on impact. This 21.5 m of crush would generate an average deceleration of 3 m/s^2, or about 0.3 G. The energy dissipated, equivalent to 30,000 cars crashing (in the 4 seconds required to complete the crushing), would have made an enormous noise. Those in the 92% of the liner that was not crushed by the impact would have experienced a mild deceleration, not too unlike that of a car or train coming to a gentle stop. Anyone in the portion that was crushed would likely have been killed or seriously injured. As few crewmembers, and even fewer passengers, would be close to the front of the ship at near midnight on a cold night, casualties would have been light. The ship would have been in no danger of sinking because of its watertight compartment structure. It would likely have returned to its maker in Belfast for repairs, and today almost nobody would have heard of it.

Crashworthiness and crash prevention

Neither builder nor owner ever used the term "unsinkable." However, the claim of a high level of design safety was well justified, notwithstanding many later questions about the quality of the steel sheeting, the absence of tops on the watertight compartments, and the number of lifeboats. The *Titanic* contained the best crashworthiness that had ever been engineered into a ship. However, engineering safety must be viewed in the context of the way it is used. Interactions between crashworthiness and crash avoidance are examples of more general behavior feedback effects (or technology/human interface effects) that are important in safety.[15-17] Changes in any factor tend to generate changes in all the others. Every piece of the safety puzzle tends to connect with many others. Less confidence in the *Titanic*'s crashworthiness would likely have led to more caution on the bridge. Shakespeare writes, “Best safety lies in fear.” (*Hamlet*: Act I, Scene 3). Because of the unsafe ice conditions, many less safe vessels spent the night still in the water waiting for better sailing conditions after sunrise.

Number of fatalities – reliability of data

Immediately after the sinking, official inquiries were conducted by a special committee of the US Senate (because American lives were lost) and the British Board of Trade (under whose regulations the *Titanic* operated). The total numbers of deaths established by these hearings were:[18]

US Senate committee:	1,517 lives lost
British Board of Trade:	1,503 lives lost

Confusion over the number of fatalities was exacerbated by the official reports to the US Senate and the British Parliament that revised the numbers to 1,500 and 1,490, respectively. Press reports included numbers as high as 1,522. Additional revisions cement the conclusion that we will never how many people died on the *Titanic*. (We do know that there were 705 survivors).

The uncertainty regarding the number of deaths on the *Titanic* alerts us to the likelihood of uncertainties in even the most seemingly reliable data. At some intuitive level, one might expect the number of deaths to be generally determinable without mistake. For various reasons, this is rarely the case. While there is uncertainty associated with fatality data, such data constitute, by far, the most reliable safety data available. Hence, much of the scientific study of traffic safety focuses on fatalities.

Number of lives lost – influence on public interest and concern

Another general safety lesson from the *Titanic* – the total number of lives lost is not the primary influence on our thoughts. This is important because if people see a problem as important they are more willing to support the cost and possible inconvenience of countermeasures. After the sinking of the *Titanic* many safety measures were enacted which are still at the core of passenger safety at sea – yet it is not clear how many lives, if any, they have saved.

In January 1945, the German troop carrier *Wilhelm Gustloff* was sunk by a torpedo fired from a Russian submarine with the loss of about 10,000 mainly civilian lives.[19] (There is much uncertainty about the total, but certainly about six times as many perished as on the *Titanic*). Nor is the overriding criterion the nation of origin or the nationality of the victims. The largest number of deaths in an airship resulted from the crash of the US Navy helium-filled dirigible *Akron* in 1933[20] The 73 lives lost were more than twice as many as the 36 lost in the vastly more famous 1937 *Hindenburg* disaster. Four airship crashes (one

US, one French, and two British) each produced greater loss of life than the *Hindenburg* crash. All these losses are, of course, minor compared to losses in war and in traffic.

Terminology

The above discussion has introduced a number of terms, which we now discuss more formally.

Traffic safety

The term *traffic safety* is used widely by specialists and the public. Such use rarely generates serious misunderstanding even though there is no precise, let alone quantitative, definition of traffic safety. The general concept is the absence of unintended harm to living creatures or inanimate objects. Quantitative safety measures nearly always focus on the magnitudes of departures from a total absence of some type of harm, rather than directly on safety as such. Depending on the specific subject and on available data, many measures are used. As mentioned above, in this book the term *traffic* will be confined to vehicles with engines traveling on wheels along public roads.

Crash

A vehicle striking anything is referred to as a *crash*. The widely used term *accident* is considered unsuitable for technical use.[21-26] *Accident* conveys a sense that the losses are due exclusively to fate. Perhaps this is what gives *accident* its most potent appeal – the sense that it exonerates participants from responsibility. *Accident* also conveys a sense that losses are devoid of predictability. Yet the purpose of studying safety is to examine factors that influence the likelihood of occurrence and the resulting harm from crashes. Some crashes are purposeful acts for which the term *accident* would be inappropriate even in popular use. At least a few percent (perhaps as much as 5%) of driver fatalities are suicides.[27,28] There is a body of evidence that media reports of suicide generate copycat suicides,[29,30] including by motor vehicle,[31,32] which provides the most socially acceptable and readily available means. Although the use of vehicles for homicide may be less common than in the movies, such use is certainly not zero. Popular usage refers to *the crash of Pan Am flight 103*, now known to be a purposeful act and therefore no *accident* in any sense of the word. Even more so, the events of 11 September 2001 were known to be intentional acts immediately after the second plane crashed into the World Trade Center. There is ongoing discontinuance of the word *accident.* In 2001 the British Medical Journal prohibited the use of the term in its publications,[26] and in 1999 the NHTSA renamed various data files. For example, the former Fatal Accident Reporting System had its name changed to the present Fatality Analysis Reporting System, thus preserving the acronym FARS. The traffic engineering profession is proving a slower learner on this matter.

Factors rather than cause

The term *cause* is used cautiously because it can too easily invoke the inappropriate notion of a single cause, such as is common in the physical sciences. Crashes result from many factors operating together. To say that the loss of life on the *Titanic* was caused by the absence of a mandatory retirement age for captains, the owner being on board, the lookout being not alert enough (or too alert), by climate conditions, or by poor quality steel may generate more confusion than clarity. Instead of focusing on a single cause, we generally think in terms of a list of factors, which, if different, would have led to a different outcome. The goal in safety analysis is to examine factors associated with crashes with the aim of identifying those that can be changed by countermeasures (or interventions) to enhance future safety.

Passengers, drivers, occupants

Any person in (or in the case of a motorcycle, on) a vehicle is referred to as an *occupant*. For the vehicles that form the main subject of this book, occupants are either *drivers* or *passengers*. Using the term *passenger* to include passengers and drivers leads to needless confusion. For example, US Government data compilations apply the term *passenger miles* to different transportation modes.[33] While it is clear that drivers are included for personal automobiles and motorcycles, it is not clear who is included for taxis, busses, aircraft, rail, etc. Different vehicles can include various categories of occupants (passengers, drivers, flight crew, cabin crew, stowaways, hijackers, etc). Although the term *passenger car* rarely causes much confusion, it is particularly inappropriate because most *cars* (the preferred term) travel with zero passengers.

Data, airbag, age, GB, gender, consequences of crashes

Collections of observed numbers are referred to as *data* and not *statistics*. Since statistics is the name of a branch of mathematics dealing with hypothesis testing and confidence limits, using it to also mean data invites needless ambiguity. *Data* will always be treated as plural (singular is *datum*). Treating *airbag* as one word is a clear choice – it shortens, simplifies, and avoids ambiguities.

We follow common usage in referring to ages – *age 20* means people with ages equal to or greater than 20 years, but less than 21 years. This is plotted at 20.5 years, very close to the average age of 20-year-olds; 40-year-olds are not quite twice as old as 20-year-olds, which might come as good news to some!

British data and laws are sometimes for the entire United Kingdom, sometimes for Great Britain, sometimes for England and Wales, and sometimes for England. Accuracy is compromised in favor of simplicity by using *GB* in this book on many occasions when *UK* is correct. Likewise, this book uses only *gender*, even in cases in which *sex* would be more correct.

The consequences of crashes include fatalities, injuries and property damage. Useful terms encompassing all of these are *harm* and *losses*. *Casualties* means injured plus killed. Context determines whether *injured* excludes fatally injured.

Crashworthiness and crash prevention

Measures that reduce harm can be placed into two distinct categories.

- **Crashworthiness**, or *crash protection*, refers to engineering features aimed at reducing losses, given that a specific crash occurs. Examples include padding the vehicle interior, making structure that is not close to the occupant crumple during the crash while keeping the occupant compartment strong to prevent intrusion of struck objects, and devices such as airbags and collapsible steering columns. Reducing risks of post-crash fires (and in the case of ships, of sinking after crash impact) are crashworthiness features.

- **Crash prevention** refers to measures aimed at preventing the crash from occurring. Such measures may be either of an engineering nature (making vehicles easier to see, better braking, radar, etc.) or of a behavioral nature (driver selection, training, motivating and licensing, enforcing traffic laws, etc.).

Comparison of effectiveness of crashworthiness and crash prevention

A fundamental difference between crashworthiness and crash prevention is that when a crash is prevented all harm is reduced to zero. Improved crashworthiness rarely eliminates all harm, but instead reduces the level of harm (say, converting a fatality into quadriplegia, or quadriplegia into paraplegia, or an expensive vehicle repair into a less expensive repair). The finding that safety belts reduce car-driver fatality risk by 42% means that a population of unbelted drivers sustaining 100 driver fatalities would have sustained 42 fewer if all drivers had used belts. However, the 42 survivors would sustain injuries, in many cases very severe injuries. Crashworthiness is measured by the percent reduction in risk for some specific level of injury, such as fatality or minor injury. A crash prevention measure that reduces crash risk by some percent is necessarily a far more effective intervention than a crashworthiness measure with the same percent effectiveness.

Less-motorized countries

Countries containing few vehicles per million population are central to many studies. The term *less-motorized countries* is a straightforward way to refer to such countries. Yet all too often the designation *developing countries* is used without justification or explanation. A common indication of development is growth of Gross Domestic Product. By this measure, the countries of North America and Western Europe are developing, while many less-motorized countries are not. Technical writing should strive for simple value-free terms, resisting the currently fashionable intrusion of Orwellian language aimed at furthering political agendas at the expense of accuracy and clarity.

Units

Given the high level of uncertainty intrinsic in many traffic safety studies, it is important to avoid injecting extraneous confusion and ambiguity from other sources. Accordingly, when questions of units arise, I have tended to be explicit. The workings of nature are, of course, independent of units. An intelligent visitor from another galaxy could accurately predict when a dropped object would strike the ground using the same physical laws familiar to us. However, the numerical values used in the calculation would have nothing in common with values in a calculation performed by an earth inhabitant.

The core of science is quantification, which requires measuring values of quantities, or variables. Variables should, to the extent practicable, be considered without regard to their units of measurement. For example, *fatalities for the same distance of travel* is preferred over *fatalities per billion kilometers of travel*. The statement that fatalities for the same distance of travel tends to decline by about 5% per year is independent of the units in which distance is measured. Thinking about variables without regard to the units in which they are measured is universal in science, and common in general usage. For example, one asks for a person's height, an appropriate variable name; one does not ask for their inchage or meterage. The answer must contain units, but units need not appear in the question. Sometimes it is impractical to avoid using units in table column headings or in names of variables, such as fatalities per year; here the unit of time is so universal that little confusion can result.

The term *billion* will be used, as in the US, to mean one thousand million, or 10^9. The "British billion", still occasionally used in Britain and Continental Europe is 10^{12}, a thousand times as large. So it is not true that everything is bigger in the US!

Another reason why throughout the book I am particularly explicit about units is the hope that by doing so I might help encourage a more unified and rational practice. Such optimism probably merits the same dismissal as Dr. Samuel Johnson's description of a second marriage as "the triumph of hope over experience." I have tended to use the SI system, the internationally agreed-upon metric system of units which is accepted by most of the world's countries but rarely used correctly in any of them. For topics in which British or US data are particularly relevant I generally use the customary units of those countries. For some topics the awkwardness of mixed units was unavoidable.

Simple questions without simple answers

Such simple safety questions as "Is this type of vehicle safer than that type of vehicle?" or "Are women safer drivers than men?" often arise. The questioners are usually disappointed when informed that the question is a lot more complicated than it appears. We illustrate the problem with a different simple question to which most of us do know the answer. Is it safer to keep a pet crocodile or a pet dog?

Figure 1-2. Which are more dangerous – dogs or crocodiles? (Cartoon by Ray Vogler, reproduced from Reference 34).

Is it safer to keep a pet crocodile or a pet dog?

If one knew little about crocodiles or dogs, the first thing to do would be to consult data, where one would find that far more people are killed per year by dogs than by crocodiles. It would be unwise to conclude that such a clear difference justified favoring a pet crocodile over a pet dog on grounds of safety.[34] Even after recognizing that fatalities per year is not an appropriate measure, the way to proceed is far from obvious. Human fatalities per animal appears a better, yet still flawed, measure. People approach close to dogs, but keep far from crocodiles. Even if one normalized for proximity, the problem remains that even without the benefit of data-based studies, people exercise more care near crocodiles than near dogs. So, all in all, it would be very difficult to answer the question “Is it safer to keep a pet crocodile or a pet dog?” based on comparing fatalities from dog and crocodile attacks.

The problem of exposure

The example above illustrates that knowledge about the numbers of persons injured at some level is rarely sufficient to answer specific traffic safety questions without an appropriate measure of *exposure* – the numbers exposed to the risk of being injured. There is no all-purpose definition of exposure; it always depends on the question being addressed. If we want to know if more males or females are killed in traffic crashes in the US, the answer is simply the count of the number of deaths. The answer is unmistakably clear – more males are killed. We may want to know how the risk per capita depends on gender – then again, using population data, we find the equally clear answer that there are more male deaths per capita than female deaths per capita. This does not address how the risk of crashing for the same distance of travel depends on gender. To do this we compute the number of deaths for the same distance of travel, and find little difference depending on gender. This provides a measure of the rate for the same distance of driving, but not for the same distance of driving under identical driving conditions. As it is likely that males do more driving under more risky conditions (while intoxicated, at night, in bad weather, etc.), these additional factors might also be considered part of the measure of exposure.

Assume that it turned out that one gender did have a higher crash rate under identical driving conditions, but that it is suggested that this is due to faster driving under the same conditions, and that this should be incorporated into the measure of exposure. Suppose that when this is done, a difference in fatality rate is now thought to be due to one gender being more vulnerable to death from the same impact, and that this also should be normalized. It should be apparent that this process must ultimately end in the rates being identical, and the vacuous conclusion that when you correct for everything that is different, there cannot be any differences!

All measures are rates

Because of the above considerations, it is probably best to use the term *exposure* sparingly, and with caution. One should certainly not use the frequently occurring expression that some measure is "corrected for exposure."

The quantities that can be measured in traffic safety are nearly always rates. That is, some measure of harm (deaths, injuries, or property damage) divided by some indicator of exposure to the risk of this harm. Simple counts are almost never used. The annual count of fatalities is a rate, namely, the number of fatalities per year. Rates related to driver deaths include the number of driver deaths per head of population, per registered vehicle, per licensed driver, or per same distance of travel.

There is no one rate that is superior to others in any general sense. The rate to be selected depends on the question being asked – and often also on what data are available. What is important is to specify exactly what rate is measured and how it relates to the problem being addressed.

Poisson distribution

Much of this book deals with factors that affect crash risk. This implies that crashes are not just random events. However, crashes do have important random components. It is therefore instructive to examine what properties crashes would have if they were perfectly random events. Such an examination provides a reference and framework to better interpret what is observed in actual crashes.

Perfectly random process can be well described and analyzed using a simple mathematical formalism called a Poisson process,[35] named for its originator, the French mathematician Siméon Denis Poisson (1781-1840). This can be explained in an example in which we assume that all drivers have the same average crash rate, λ, per some unit of time. If λ were 0.1 crashes per year, then drivers have, on average, 1 crash in 10 years, or 2 crashes in 20 years, and so on. The underlying assumption for Poisson processes is that the observed risk of crashing is the result of a uniform risk of crashing at all times (a 0.1 probability of crashing per year means a 0.1/365 probability of crashing each day, and so on). If all drivers have the same probability of crashing each day, at the end of a year all will not have the same number of crashes because of randomness. The Poisson distribution enables us to compute the probability, *P(n)*, that a driver will have precisely *n* crashes during a period of *N* years as

$$P(n) = \frac{(\lambda N)^n e^{-\lambda N}}{n!} \qquad \text{1-1}$$

where *n!* (n factorial) means $1 \times 2 \times 3 ... \times n$ and λ is the crash rate in crashes per year. Rather than thinking of *P(n)* as the probability that an individual driver has *n* crashes, we can think of it as the fraction of drivers from a population of identical drivers who will have *n* crashes. Substituting $\lambda = 0.1$ into Eqn 1-1 gives that in one year (that is, $N = 1$) 90.48% of drivers are crash free, 9.05% have one crash, 0.45% have two crashes, and 0.02% have three or more crashes. This and other examples are presented in Table 1-1.

The actual number of crashes per year experienced by the 190,625,000 drivers[2] in the US is estimated[8(p 9)] to be 16,352,041, giving an average driver crash rate of 0.0858 crashes per year (equivalent to an average interval between crashes of 11.7 years). If crashes were a Poisson process, 91.78% of drivers would enjoy a crash-free year. Purely by chance, 0.01% of drivers (19,000 drivers) would experience three or more crashes. In the following year these 19,000 drivers would have the same crash risk as the overall population. Removing them from the driving population would not change the overall crash rate. It would reduce the number of crashes because there would be fewer drivers, but the reduction would be the same if 19,000 drivers chosen at random were removed, or for that matter, if 19,000 crash-free drivers were removed.

The example that a driver has only a 1.629% chance of being crash free after 48 years of driving ($N = 48$) at the average risk will be used later (p. 359).

Table 1-1. Probability (percent) of having exactly *n* crashes in *N* years if the average number of crashes per year is λ.

- **The last column shows observed California data with an average crash rate of 0.0625 crashes per year.[36]**
- **All the other values are calculated using Eqn 1-1.**

	λ =	0.1	0.0858	0.0858	0.0858	0.0625	*0.0625*
	N =	1	1	10	48	1	*1*
n							
0		90.484	91.780	42.409	1.629	93.923	*94.135*
1		9.048	7.873	36.379	6.705	5.880	*5.500*
2		0.452	0.338	15.603	13.805	0.184	*0.341*
3		0.015	0.010	4.462	18.947	0.004*	*0.024**
4		0.000	0.000	0.957	19.504		
5				0.164	16.061	* 3 or more	
6				0.023	11.022		
7				0.003	6.483		
8				0.000	3.337		
9					1.527		
10					0.629		
11					0.235		

"Accident proneness"

The observation that some individuals experience a much larger than average number of industrial injuries or traffic crashes gave birth to the notion of *accident proneness* in the early decades of the twentieth century. Those with elevated numbers of crashes were designated *accident prone*, and it was claimed that prohibiting them from driving would substantially improve safety. The notion became thoroughly discredited in the face of greater appreciation of the statistical properties of crashes and when empirical studies failed to find that drivers with a large number of crashes in one period had an appreciably above average number in subsequent periods.

The dismissal of the notion of *accident proneness* has generated some confusion. What is discredited is the notion that an above average number of crashes in one period, by itself, can provide sufficient predictive power to be useful as an effective safety policy measure. However, dismissing the notion of *accident proneness* does not mean that individual drivers, or groups of drivers, cannot be reliably identified by other methods as posing greater than average driving risks. Indeed, that is a central theme of this book. For example, it can be predicted with confidence that an individual driver convicted of many traffic-law violations will have higher future crash risks if permitted to continue to drive, and it can be predicted with near certainty that a group of 20-year-old male drivers will have higher than average crash rates.

Comparison with observed data

The last two columns in Table 1-1 show predicted crash frequencies assuming a Poisson process and observed frequencies, based on a data set in which the average crash rate for all drivers was 0.0625 crashes per year.[36] The Poisson prediction reproduces the general pattern, but with important departures. The observed data have a greater percent of crash-free drivers than predicted, and six times as many drivers with three or more crashes as predicted. Such departures indicate major departures from the assumption that all drivers have the same crash risk. One might suggest that 1/6 of the drivers with three or more crashes were average drivers who were unlucky, while the other 5/6 arose from a population with above average crash risk. However, it is not possible to determine, based on crash-frequency alone, whether any individual driver is in the three or more crashes category due to bad luck or risky driving. The very same randomness keeps many of the high-risk drivers crash free. Assuming that different subsets of the total driving population have different values of λ can reproduce the observed distribution.

Computing errors from Poisson processes

Many safety analyses rely on counts of items, such as the number of single-vehicle crashes or number of driver fatalities. By assuming that observed numbers originated from a Poisson process we can estimate errors. Suppose there is, on average, one crash per day, so that after n days we would expect n crashes. However, a rate of one crash per day may produce more or fewer than n crashes in n days because of randomness. Many replications will produce an average value of n. For a Poisson process, the standard deviation of this distribution is equal to $\sqrt{n}$, and when n is reasonably large (say, more than about 6), the distribution is close to the normal distribution, which has convenient properties. An observed n fatalities in a month is interpreted to arise from a process generating fatalities at a rate of $(n \pm \sqrt{n})$ fatalities per month, where the error is one standard error. In this book all quoted errors are standard errors, a common practice in science. There is a 68% probability that the true value is within one standard error, and a 16% probability that it is either higher or lower. Errors in the literature are often given as two standard errors – there is a 95% probability that the true value is within two standard errors.

If we observe that a particular vehicle model, say car_1, has $n_1 = 100$ crashes in a year, then there is a 68% probability that the process generating these crashes is doing so at a rate of between 90 per year and 110 per year, or (100 ± 10). If we observe that car_2 has $n_2 = 110$ crashes, the car_2 rate is (110 ± 10.49). The rates for the two models overlap when the errors are included, suggesting an absence of strong evidence that car_1 is safer than car_2. More informatively, we can compute the car_2 risk, R_2, relative to the car_1 risk, R_1, as

$$\frac{R_2}{R_1} = \left(\frac{n_2}{n_1} \pm \frac{n_2}{n_1}\sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \right) = 1.100 \pm 0.152 \qquad \text{1-2}$$

which may be expressed by saying that the car_2 risk is $(10 \pm 15)\%$ higher than the car_1 risk. This is the type of quantitative answer that is informative and useful, and should be sought. Statements to the effect that there is no statistically significant difference between the risks for the two cars are of no value, yet they pervade safety and other literature. Based on principles of reason and logic, it is essentially certain that one of the models is safer than the other. The fact that the result failed to show any difference is a comment on the study, not on the relative safety of the two models. From the quantitative result we can be very confident that the risk in one model is not 50% higher than in the other, whereas the statement that there is no statistically significant difference justifies no such conclusion.

If four later studies reported quantitative results $(-3 \pm 13)\%$, $(11 \pm 7)\%$, $(16 \pm 20)\%$, and $(12 \pm 8)\%$, combining all values gives[37] that car_2 risk is $(9.8 \pm 4.5)\%$ higher than car_1 risk, a result providing evidence that car_2 risk exceeds car_1 risk by an important amount. If all of the studies had reported merely no statistically significant difference, then, collectively, the value of the studies would be, at best, worthless. The value of the studies would be less than zero if someone were to conclude that many studies reporting no statistically significant effect provides strong evidence that there is really no effect! The goal of science, namely quantification, cannot be achieved by results presented only in terms of non-quantitative hypotheses that meet some standard, no matter how stringent, of statistical significance.

Three levels of knowledge

Because the goal of quantification with specified error limits is not always attainable, it is helpful to distinguish three levels of knowledge:

1. Not based on observational data.
2. Hinted at by observational data.
3. Quantified by observational data.

It might seem surprising that the first level should appear at all in any effort focused on technical understanding. Yet there are many cases in traffic safety and in other aspects of life in which we have confident knowledge not supported by a shred of observational data. The policy that is at the very core of pedestrian safety is such a case. Pedestrians are advised to look before crossing the road.

There are no observational data showing that it is safer to look than not to look, nor is it likely that the question will ever be addressed experimentally. Even in the absence of empirical evidence, I nonetheless look myself, and consider it good public policy to vigorously encourage everyone to do likewise.

Such a conclusion is based on reason and judgment. Most people agree that it would be foolish to suspend judgment until a study satisfying strict standards of rigor is published in the scientific literature. There are many important traffic safety problems where reason and judgment are our only guides. When this is all that is available, there is nothing shameful about using it, provided that the basis for the belief is apparent.

Differences in traffic are immediately apparent between different countries, but are not quantified, and would in fact be difficult to quantify in a way that would capture well what the eye immediately perceives. Traffic in Cairo, Egypt looks much different from traffic in Adelaide, Australia in ways that must surely contribute to the much greater safety in Adelaide (Fig. 13-2, p. 335).

The second level of knowledge occurs when there are data, but for various reasons the data do not support clear-cut quantitative findings. The problem is generally that using the data to make inferences requires assumptions of such uncertainty that more than one interpretation is possible. Another problem could be that there are too few data to support statistically confident conclusions. This is less common, but cited more often. Experience with research methods, knowledge of the literature, and long-term immersion in the field are the best tools to arrive at appropriate conclusions when information is loosely structured and questionable.

The firmest knowledge flows from the third level, the one to which we always aspire. That goal is captured in the often-quoted words of physicist Lord Kelvin (1824-1907), for whom the absolute temperature unit, degrees K, one of the seven basic units in the SI system, is named:

> *I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science, whatever the matter may be.*

Summary and conclusions

Traffic crashes are a major world public health problem. More than a million people are killed on the world's roads annually, more than 40,000 in the US. Injuries vastly outnumber deaths. The problem is all the more acute because the victims are overwhelmingly young and healthy prior to their crashes. The magnitude of the problem is grossly underemphasized, in part because large numbers of deaths occur every day and are accordingly not newsworthy in the way that an unusual harmful event killing far fewer people is.

Interventions adopted to reduce harm from crashes are of two types. Crash prevention reduces harm by preventing the crash from occurring, while crashworthiness interventions reduce the harm produced when a crash does occur. Traffic law aims at preventing crashes, while softer interior surfaces and airbags aim at reducing harm when crashes occur. Preventing 10% of crashes provides more benefit than a crashworthiness measure that reduces fatality risk by 10%. This is because crashworthiness measures typically convert fatalities prevented into serious injuries, whereas when the crash is prevented, all harm from it is prevented.

Traffic safety is measured using rates – one quantity divided by another. Common examples are fatalities per year, fatalities per thousand registered vehicles, and fatalities per billion km of vehicle travel. Different rates address different questions – no one rate is superior to others in any general sense. Some simple questions are difficult to answer because of the problem of exposure. The number of people hurt is known, but the extent to which they are exposed to the risk of being hurt is not known.

Properties of a hypothetical population of identical drivers all having the same risk of crashing every day can be computed using the Poisson distribution. Due to randomness alone, some drivers will have two, three or even more crashes at the end of a year, while other "identical" drivers will be crash free. Removing the high-crash drivers from such a hypothetical population has no effect on average crash risk the next year. All drivers do not have equal crash risks, but the expected random variation in numbers of crashes if they did makes license revocation based solely on above-average crash experience a relatively ineffective countermeasure.

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