Concise Theory of Road Safety

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T. P. Hutchinson

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What this book is about

If you say that road safety is very much a data-driven subject, I will agree with you. But theory is needed, particularly because of the many deficiencies of road safety data, and because it makes thinking easier.

So far as this book is concerned, theory means the following topics.

- The detection of, and the reaction to, emergencies. That is, the subject is the last second or so before the vehicle strikes something. An important example is the operation of AEB (autonomous emergency braking) systems. This term refers to technologies fitted to a vehicle that detect an obstacle and, without command from the driver, brake the vehicle as strongly as possible.
- The impact of the human with a vehicle (either the exterior or the interior). A vehicle's front (e.g., the bonnet) should act as a cushion for pedestrians and other unprotected road users, being soft in comparison with the very stiff structures under the bonnet, and a vehicle's interior (including the restraint systems) should act as a cushion for the occupants.
- Generalisation from a test to the real world: a test of a vehicle (one simulating a pedestrian impact, for example) is in specified conditions, but many other sets of conditions (many other speeds, for example) occur in real-world accidents.

The attitude in this book is to say let's start with the last instant before impact. It is found empirically (that is, from data) that the effect of speed on the probability of death is strong. A theory is quite likely to be useful even if it applies only to the fraction of a second before impact, as vehicle braking can be sufficiently sharp that a fraction of a second is enough for a worthwhile reduction in impact speed to take place.

The complete behaviour of a driver or of a driverless car is outside the scope of the book.

T. P. H.

To a large extent, this book is a shortened version of "Road Safety Theory" RoadSafetyTheory.com, which is also by T. P. Hutchinson and was published in 2018.

There is also some overlap between the contents of this book and "Blunt Injury and Damage: Theory to Interpret Data" BluntInjuryandDamage.com, by T. P. Hutchinson and published in 2018.

Contents

1. Introduction

1.1 The approach taken in this book, and the reasons

This book takes a particular view of what is meant by a theory of road safety. It is a view that I have been led to by technological developments over the past ten years or so. Specifically, there are autonomous vehicles on the roads in some places, and some vehicles with limited autonomous functions (in particular, braking) on the roads in many places.

- Autonomous functions, as with other vehicle systems, require testing.
- Testing generates data.
- Humans want to describe and understand the data.
- Theory, or modelling, is potentially very helpful in understanding data, and in predicting how the vehicle will behave in conditions that are not tested --- at other speeds, for example.

A theory is quite likely to be useful for describing real accident events, as well as for modelling test data.

The theory that I will describe is simple, and could have been written down 50 or 100 years ago. But, as far as I know, it wasn't. The autonomous operation of vehicle systems is what has pushed me into making simplifications, and perhaps over-simplifications, of what happens. The theory is most relevant to what I will call typical or ordinary impacts. By this, I largely mean frontal impacts. See section 1.4 and chapter 3 for more on this.

For damage of objects (rather than injury of humans), see Hutchinson (2018b).

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- The detection of, and the reaction to, emergencies. That is, the subject is the last second or so before the vehicle strikes something. An important example is the operation of AEB (autonomous emergency braking) systems. This term refers to technologies fitted to a vehicle that detect an obstacle and, without command from the driver, brake the vehicle as strongly as possible.
- The impact of the human with a vehicle (either the exterior or the interior). A vehicle's front (e.g., the bonnet) should act as a cushion for pedestrians and other unprotected road users, being soft in comparison with the very stiff structures under the bonnet, and a vehicle's interior (including the restraint systems) should act as a cushion for the occupants.
- Generalisation from a test to the real world: a test of a vehicle (one simulating a pedestrian impact, for example) is in specified conditions, but many other sets of conditions (many other speeds, for example) occur in real-world accidents.

So that is what I mean by road safety theory. There are two main reasons why the content of this book is as it is. Firstly, it is found empirically (that is, from data) that the effect of speed on the probability of death is strong. Therefore, there is the prospect of a theory being useful even if it applies only to the fraction of a second before impact: vehicle braking can be sufficiently sharp that a fraction of a second is enough for a reduction in impact speed to take place --- I mean, a reduction that is large enough to be worthwhile in respect of reducing the probability of death. Secondly, testing is very important in ensuring and monitoring the safety of manufactured goods. I am thinking chiefly of vehicles. A crash test or impact test is typically conducted in a closely-specified set of conditions. It is desirable to also get information that is relevant to other sets of conditions --- and a theory is almost certainly needed for this.

There is not much in this book about the initiation or causation of an emergency: for example, whether something moved into the path of the vehicle, or whether there was loss of control. Nevertheless, a few comments will be made in chapter 4.

A few more examples of topics that you might think would be in this book, but to a large extent are omitted, are bad decisions, misjudgments, skills, risk-taking (by adults, young adults, children), recklessness, tyre-road interaction (on dry roads, wet roads, gravel roads), vehicle overturning, sight lines, visual complexity. And this book is micro level, not concerned with predicting the effects of changes to education or publicity or law or enforcement of law in regard to traffic and vehicles, or with choices of expenditure by a road authority (about where on the road network to make improvements, for example), or with concepts like accident rates. (An accident rate is the number of accidents divided by some measure, such as distance driven, of exposure to the risk of an accident. See Appendix 5 for a little on accident rates.)

The attitude in this book is to say forget about what we want, let's start with the last instant before impact, there is good reason to think a theory may be useful even if it only refers to that. In contrast to that instant, the complete behaviour of a driver or of a driverless car is outside the scope of the book.

1.2 The main line of argument

For many road accidents, what is said in this section is mostly correct. (These cautious words are a reminder that a great many peculiar events occasionally do occur in road accidents.)

1.2.1 The impact

Severity of injury is strongly influenced by the following.

- What the human hits (in particular, its stiffness).
- The speed of the impact.

A pedestrian may be hit by the exterior of a car. A driver or passenger may hit the interior of a car. The properties of what the human hits are the concern of engineers and materials scientists, perhaps even more than of specialists in road safety. Impact speed, on the other hand, is undoubtedly a mainstream road safety topic.

Only two factors have been listed here. The following might have been included. (a) Instead of "the human", the part of the body might have been specified. The head is the most important. (b) Instead of "stiffness", several types of stiffness might have been listed. (c) The angle of impact. An impact at right angles to the surface of what the human hits is the most important. Or, I could say, the component of the relative velocity that is at right angles to the surface is the velocity that matters most. (d) Characteristics of the human. These might be collected under the term "frailty". In particular, they affect the condition of the human some weeks and years after the impact. But we cannot change them in the way we might change stiffness or speed, and that rather limits their interest to us.

See also section 9.6.

1.2.2 The last seconds before the impact

Impact speed being very important in determining whether the road user dies, or how serious the injury is, what are the factors affecting impact speed?

A vehicle is travelling normally. Some emergency arises. There may be braking. An impact occurs.

- That may be with a pedestrian (or other human outside a vehicle, such as a pedal cyclist or a motorcyclist).
- Or the impact may be with a vehicle or a roadside object, with the impact of vehicle occupants with the interior of the vehicle occurring a fraction of a second later.

That rough description makes clear that the following are likely to be important for whether there is an impact, and, if so, at what speed.

- Detection of the emergency by the driver. How early this occurs is important.
- Decision on what action to take (e.g., strong braking). How quickly this occurs is important.
- If braking is the action, strength of the braking is important.

(As already noted, detection-decision-action may be by autonomous operation of the vehicle, rather than by a human.)

1.2.3 What's the use of theory?

You may think that the purpose of a theory is to tell us the answer if we do not have direct empirical knowledge of a question. I do not positively disagree with this. Theory in this book is of some value in suggesting that at a late stage in the sequence of events, only a limited number of things affect outcome: travelling speed, how early danger is appreciated, reaction time, strength of deceleration.

The biggest merit of theory, however, is that it helps organise data, plan experiments, and stimulate thought. And comparison of theory with data very often draws attention to a theory's problems, or draws attention to problems with the data, or suggests something happened that was not expected.

Data is useful. But you should not put it under pressure that is too much for it. When you examine data carefully, you often find something is wrong with it. That is an important reason why theory is needed, to help us perceive the correct message in imperfect data. That applies to both crash numbers (as routinely recorded by the police), and to data collected in experiments.

1.3 Organisation of this book

In section 1.1, the following three topics are identified as the most important in this book.

- The detection of, and the reaction to, emergencies. That is, the subject is the last second or so before the vehicle strikes something. For this, see chapters 5 and 6.
- The impact of the human with a vehicle (either the exterior or the interior). For this, see chapters 9 and 10.
- Generalisation from a test to the real world. For this, see chapter 11.

The other chapters are as follows.

- Chapters 1 - 4 are preparation for the main part of the book.
- Chapters 7 and 8 describe the movement of vehicles in collision, and the movement of their occupants.
- Chapters 12 and 13 end the book with a few pages on road accident research and improving road safety.

Appendices 1 and 2 list the chapters of two other books by the present author: "Road Safety Theory" and "Blunt Injury and Damage: Theory to Interpret Data".

There are five further Appendices.

1.4 Comments on the approach and contents of this book

There may not be a need for theory if modern vehicle safety technologies (autonomous and connected vehicles) are very successful. In limited respects, I think there will be great success. But I do not think they will be viewed as solving the road accident problem. One of my reasons is that I think new technologies will be so effective for some tasks that the extra improvements from further development will not be perceived as good value for money. I should say that I do not know the details of the operation of new technologies.

An obvious difficulty with a book on road safety theory is that there are many types of road accident, and many factors contribute to the causation of some road accidents. I am chiefly concerned with typical road accidents and generalities about them. See especially chapter 3 for explanation of what I mean. Perhaps I should say typical impacts, rather than typical accidents. Consider right-angle crashes: for the striking ("bullet") vehicle, there is a fairly typical frontal impact; for the struck ("target") vehicle, there is a side impact and there may be substantial intrusion into the occupant compartment. The impact will be an unusual one for the target vehicle, as discussed in chapter 3.

I would be very upset if my concentration on "typical" road accidents led to any neglect of other types: most of the various other types are individually comparatively uncommon, but countermeasures to them may be very worthwhile. And there are many specialised methods of attempting to prevent or mitigate particular types of accident, whether typical or unusual. Many of these specialised methods are important and cost-effective, even if they are relevant to only a comparatively small proportion of accidents.

The final point I want to make at this stage is that real people are being killed and seriously injured. I deal with statistics and data on the subject. I write about the subject impersonally. People working in research are accustomed to this style. But I hope that many people outside research will read this book. Some of them have personal experience of road accidents and the consequences. This book may seem far distant from the suffering they are familiar with. I hope they will not reject this book if that is so.

1.5 The technical level of this book

This book will use mathematics --- mathematical symbols and notation, equations, and algebra. This will include some calculus --- differentiation, integration, and differential equations.

- I will do my best to explain in words the core meaning of the most important equations.
- I think an undergraduate in physical sciences, mathematics, engineering, or medicine ought to be able to understand everything in this book.

Many readers of this book, I hope, will come from outside the world of road safety study and research. And for some, it may be a difficult book. I'm not an expert on reading, and my advice can only be based on my experience when reading about something unfamiliar. Part of that advice is to press on at a reasonable rate. One can get something out of text from only partial understanding, and to a degree appreciate the facts being marshalled, the tools being used in the argument, the conclusions reached, and the soundness of the conclusions. Another part is that you should not be surprised if you sometimes spend 30 minutes reading a single page. That is what it takes when you are at the borderline of understanding --- but only do this if you really are gaining something, and it is better to move on if you find yourself staring at a paragraph without real engagement of your mind.

So why read this book if some pages may take 30 minutes? There are about 1 or 2 million deaths per year from road accidents (worldwide). If the losses of lives, the injuries, and the damage are costed the way they are in developed countries, the figure is in the tens of trillions of dollars per year. A problem of that magnitude deserves your serious attention.

1.6 Words and explanations

I live in Australia. Traffic drives on the left hand side of the road here. The driver sits on the right hand side of the vehicle. That's what I am accustomed to. I will sometimes refer to a "vehicle" and sometimes to a "car"; I will often include station wagons, SUVs, and 4WDs within the term "car". Some other things that need explaining are as below.

Primary safety and secondary safety. Primary safety refers to the avoidance of crashes, secondary safety refers to reduction of injury given that a crash has occurred. Primary safety measures include improving the brakes, handling, and conspicuity of a vehicle. Autonomous emergency braking comes into this category, too. Secondary safety measures include seat belts and air bags for vehicle occupants, and helmets. For pedestrians, vehicle fronts must not be too stiff, and improvement in this respect is another important secondary safety measure.

Velocity change and mass ratio. In typical road accidents, there is a single important impact, and injury occurs then. Velocity change refers to the change in velocity of the vehicle being considered, and is very important in determining the occupants' injury severities. Mass ratio refers to the ratio of masses of the two vehicles that are involved. This, together with the relative velocity of the vehicles, determines velocity change. For more about this, see section 2.4, section 7.2, and Appendix 3. (Velocity change is sometimes referred to as deltaV.)

Restrained and unrestrained car occupants. Restrained car occupants are those wearing a seat belt or protected by an air bag. Unrestrained occupants are those without such devices.

A pillar, B pillar. The A pillars of a car are at the left and right of the windscreen, that is, forward of the front doors. The B pillars are rearward of the front doors.

Nearside, offside. The nearside of a vehicle is that closer to the pedestrian footpath. That is, it is to the driver's left when traffic drives on the left. The offside of a vehicle is that closer to the road centreline. That is, it is to the driver's right when traffic drives on the left.

Autonomous. An autonomous vehicle is one that detects aspects of the environment and acts without input from the driver. In some places, there are fully autonomous vehicles operating among conventional vehicles. A less ambitious development is autonomous emergency braking.

Displacement, deformation, distance. These words all refer to how far something moves after initial contact with something else. Unsupported metal in the middle of a car's bonnet deforms a substantial distance (several centimetres) when struck by a pedestrian's head or shoulder. Injury is likely to be much less than if the pedestrian had hit the car's A pillar, which is very stiff and deforms very little. An instrumented headforms typically measures acceleration from moment to moment over the milliseconds of impact; and thus displacement is usually not measured directly, but by double integration of acceleration.

Translational vs. rotational movement. In physics, these terms are used in contrast: translation means movement of location.

Velocity. This term is sometimes used in a way such that it is positive in one direction and negative in the opposite direction. But sometimes it is used quite casually to mean speed.

Acceleration and deceleration. As is commonly done, I will sometimes use acceleration in distinction to deceleration, and I will sometimes use acceleration in a wider sense to include deceleration. Acceleration is often expressed in units of g, the acceleration due to gravity, which is approximately 9.81 m/sec/sec. An impact of 20 g, for example, refers to approximately 196 m/sec/sec.

Normal. (a) In the context of geometry, this often means at a right angle (90 degrees, perpendicular). An impact test may be set up so that a sphere falling vertically strikes a flat horizontal plate: the impact is normal. (b) In the context of statistics, a normal distribution is a commonly-used continuous probability distribution.

Coefficient of restitution. Referring to an impact of two bodies, the coefficient of restitution is the absolute value of the ratio of final relative velocity to initial relative velocity. Two types of impact are of most relevance to this book --- impact of a vehicle with another vehicle or an object, and impact of a human with the exterior or interior of a vehicle or with the ground. In both, the coefficient of restitution is quite small, and can sometimes be thought of as zero.

Headform. This approximates the dimensions and weight of the human head. It is instrumented with accelerometers. It is projected at a surface, such as the exterior or interior of a car. The accelerations during the milliseconds of impact are recorded and processed.

Bottoming out. Consider a hard object hitting a cushion. The hard object might be a pedestrian's head, or might be a pedestrian headform used in impact tests as described in section 9.2. The cushion might be a car's bonnet. At low speeds, the cushion will ensure that the hard object will be stopped fairly gently. But that is only the case if the cushion is sufficiently thick. If the cushion is thin, or if the impact speed is high, the whole depth of the cushion will be used up. In the case of a pedestrian head hitting a bonnet, the bonnet may deform so much that it strikes very stiff structures in the engine compartment. Consequently, for the head, there is great increase of the severity of the impact. This is referred to as bottoming out. In that case there is a sudden change in stiffness. The change may be a little less sudden in the case of foam that covers something rigid. The foam may behave linearly up to a substantial fraction of its depth, before gradually increasing in stiffness and then sharply increasing in stiffness. See also section 20.2.

Wrap-around distance. This refers to a distance from the ground vertically, and then around a car's front to where a pedestrian's head is likely to strike.

Risk compensation. This refers to the idea that if a road user perceives a situation as safe, or believes some safety device to be in operation, they may take more risks than otherwise: for example, they may drive faster. It is controversial how important this is. See also section 13.3.

Severity of injury. Data about road accidents and road casualties that is routinely collected by the police often includes a classification of severity of injury. For example, the categories used may be fatal, serious, slight, no injury. When these terms are applied to accidents rather than the people themselves, they refer to the most seriously injured person.

- Many methods of classification are used by various police forces around the world. For example, it is common for fatal injury to include deaths at the scene of the accident or within 30 days, and to exclude later deaths. It is common for serious injury to refer to injury requiring admission to hospital, or a broken bone. (The classification may be made by someone who is not a medical expert, and who is using imperfect information.)
- When reference is made to accidents or to people involved, the term "serious" may be used for brevity, and actually mean serious or worse (that is, the fatalities are included).
- The term "severity", in the context of a set of accidents or people involved rather than for an individual, is likely to refer to a proportion, such as the proportion who are killed or seriously injured.

Value of a statistical life. Some people sometimes have to make decisions about whether to spend money (on a road improvement, for example) that will probably prevent some accidents and may save some lives. The value of life (in dollars or other currency) is an aid to making that decision. The phrase "value of a statistical life" emphasises that the context is impersonal. (I expect it is hoped to avoid provoking hostility from people who say that spending any amount of money is worth doing if a life will be saved.)

Accident rate. An accident rate is a number of accidents divided by something that the number of accidents might reasonably be supposed to be proportional to. Examples: accidents per year, accidents per person, accidents per driver, accidents per vehicle, accidents per kilometre travelled, accidents per tonne of fuel sold, accidents per conflict between vehicles. The divisor is often thought of as a measure of exposure to the risk of accident.

- There are often substantial difficulties with the concept. For example, in the circumstances in which we are using it, is the divisor an appropriate one? Do we, for example, expect kilometres driven in a city (slow speeds, many other vehicles) to be equivalent to kilometres driven in the country (higher speeds, few other vehicles)?

- There are often substantial difficulties with the measurement of the divisor. Can we estimate reasonably accurately the distance driven, for example?

There is further discussion in Appendix 5.

General abbreviations. i.e. = that is, e.g. = for example, et al. = and others (this is used in text to avoid a long list of joint authors of a particular work), vs. = versus, meaning in contrast to, and also used in referring to the two axes of a graph or scatterplot (as in y vs. x).

1.7 Some terms used in mathematics, statistics, and data analysis

It is not practicable to give a short course in algebra, calculus, and statistics in this book. But I should explain a few terms.

Symbol for multiplication. Both × and the dot . are used as symbols for multiplication.

Power function, and exponent. When some number x is multiplied by itself, x × x, this is written as x^2. Similarly, x × x × x is written x^3. The expression x^c is termed a power function of x, and c is called the exponent (and is not necessarily an integer).

- Three special cases: $x^1 = x$, $x^0 = 1$, $x^{-1} = 1/x$.
- Product of powers of x: $x^b.x^c = x^{b+c}$
- Successive raising to power: $(x^b)^c = x^{b.c}$
- Product of identical powers: $x^b.y^b = (x.y)^b$

Symbol for proportionality. $\propto$ means "is proportional to".

Symbol for differentiation with respect to time. If x is distance, the rate of change of distance (speed, the first derivative of distance with respect to time) may be written as x', and acceleration (the rate of change of speed, that is, the second derivative of distance with respect to time) may be written as x''.

Logarithm. It is common to use natural logarithms rather than logarithms to base 10; ln is the abbreviation used for natural logarithm (logarithm to the base e, where e is Euler's number).

- Logarithm of a product: $\ln(a.x) = \ln(a) + \ln(x)$
- Logarithm of a power: $\ln(x^a) = a.\ln(x)$

Brackets. Brackets are used for two purposes: to group quantities together, and to denote the argument of a function.

Independent variable and dependent variable. When calculating one thing from one or two or more other quantities, the result might be known as the output or the dependent variable. The quantities from which it was calculated are the inputs or independent variables. (Independent variable is rather a poor name in the sense that one independent variable may not actually be statistically independent of others.)

Median. The median is a sort of average. If numbers (observed data) are arranged in order of magnitude, the median is the middle one. Compared with the mean, the median has some disadvantages. It also has some advantages: it is meaningful when the numbers are only ordinal, not fully quantitative; and it is less sensitive to observations that are unusually small or large (and may be in error).

Ordinal data. This refers to numbers, or other things, that can be put in order, but which it is meaningless to add or subtract. Injury severity is an important example: one method of classification might be as fatal, serious, slight, none, and another might be as 6 (maximum, virtually unsurvivable), 5 (critical), 4, 3, 2, 1 (minor), 0 (no injury).

1.8 Notation

Please be aware that notation (what symbols mean) is not the same throughout this book. A symbol such as x may be used to mean one thing in one chapter and another in another chapter.

One example is that v may refer to the velocity with which a vehicle is travelling before any emergency has been detected, and in another section of the book it may refer to impact velocity.

Another example is that there are some quantities (e.g., velocity) that are vectors. These are positive in one direction and negative in the opposite direction. I am sometimes careful about this, and sometimes not. What I mean is, suppose a vehicle was travelling at 50 km/h before impact, was in impact with a vehicle travelling in the opposite direction, and travels at 10 km/h in the opposite direction after impact.

- I might say change of velocity is 50 - (-10) = 60 km/h. (Here I am being careful to represent a change as a difference, and to represent the opposite direction by the opposite sign.)
- Or I might say change of velocity is 50 + 10 = 60 km/h. (Here I am writing casually and presuming that the description of the event is sufficient to make the change clear.)

2. The importance of speed: Empirical data

2.1 The purpose of this chapter

Vehicle speed is prominent in this book. The purpose of this chapter is to give you some idea why.

> It is widely thought among specialists in road safety that impact speed has quite a big effect on the probability of being killed, and thus on the number of people killed.

I do not intend to examine all the evidence for and against that proposition, discuss objections to some of the evidence, and discuss objections to the objections. The reason is that I do not think the proposition is controversial. Quite a small selection of evidence will be sufficient.

The proposition is often put into quantitative form in the following way.

> The probability of death (p) is a power function of speed at impact (v). That is, $p \propto v^c$, where c is the exponent of the power function and $\propto$ means "is proportional to". Furthermore, c is appreciably bigger than 1, approximately 3. (Usually v should be interpreted as velocity change, rather than velocity.)

Evidence for this dates back at least as far as Moore (1970). The data was apparently that in Wolf et al. (1969). Details are not clear: Wolf et al. were concerned with travelling speed, but Moore described v as impact speed. Fitting of a power function may have been by Moore, who gave the exponent c as 2.5.

Elementary properties of power functions mean that in the case of small changes in speed, statements like the following are true.

> If the impact speed is reduced by 1 per cent, the probability of death is reduced by c per cent.

Thus if c is about 3, the reduction in the probability of death and thus in the number of deaths is about 3 per cent for every 1 per cent reduction in impact speed. Statements like this, of course, are typically made on the basis of "other things being unchanged" (ceteris paribus).

A few words should be said about the idea of "other things being unchanged". One of the implications of this in the present context is that the number of impacts does not change. However, that may be unrealistic.

- Reductions of impact speed are typically the result of reductions of speed a moment earlier, when the vehicle was travelling normally. These earlier reductions often make impact itself less likely. In this case, the number of deaths will be reduced by more than c per cent.
- On the other hand, it may occasionally be the case that driver behaviour becomes worse (e.g., travelling speed becomes faster) when the driver knows that some safety measure is in operation. (Risk compensation is one of the terms for this. See also section 13.3.)

The claim that the effect of speed is big refers specifically to the probability of death. The effect of speed on the probability of serious injury is proportionately considerably less. See section 2.4.4.

2.2 Background

Before coming to the main parts of this chapter, mention should be made of change of speed limit, change of speed, and change in number of deaths. When speed limits are lowered, average vehicle speeds are reduced, and when average speeds fall, the number of road deaths also falls. Evidence for crash reductions from imposing speed limits on main roads outside towns dates back at least as far as Smeed (1961), whose data came from France, Germany, and Britain. A few years later, Newby (1970) concluded that "speed limits as applied in practice have nearly always led to immediate reductions in vehicle speeds and in average accident rates".

According to Nilsson (1982), the number of fatal crashes is approximately proportional to the fourth power of speed. Cameron and Elvik (2010) reviewed evidence about the strength of this relationship --- specifically, in regard to the exponent if the number of fatalities is assumed to be a power function of average speed. Their Table 4, for example, gives exponents of 4.7 and 4.3 for rural and urban environments, respectively. Cameron and Elvik concentrated on a subset of the extensive list of studies discussed by Elvik et al. (2004). See also Cameron and Elvik (2008). The basic methodology of the studies covered by those reviews is to observe changes in road crashes and deaths following changes in average speed.

The effect of mass ratio on velocity change in two-vehicle crashes is well-known. (See section 2.4, section 7.2, and Appendix 3.) Consequently, mass ratio will affect the proportion of drivers who are killed, and other measures of injury severity. Evans (2004, p. 72) refers to it as the first law of two-car crashes, proposing specifically that the dependence of probability of driver fatality on velocity change is a power function with an exponent of about 3.6.

2.3 Joksch (1993)

Joksch (1993) considers the risk of death for car drivers, as a function of velocity change.

He reports that Joksch (1983) found that this risk was approximately proportional to the fourth power of velocity change, for car-car collisions. The data came from the National Crash Severity Study (NCSS) in the U.S.A. He notes two reasons why there might be some error in this result: cases with missing velocity change were omitted, and the NCSS accidents may not have been representative.

He also reports this risk to be approximately proportional to the fourth power of velocity change in another dataset. This was the National Accident Sampling

System (NASS) in the U.S.A. For missing velocity change with this dataset, he was able to impute velocity change from the speed limit. That made a slight difference to the estimated exponent, increasing it from 3.9 to 4.1. (I cannot see any statement about whether this result applies to car-car collisions or to all car crashes.)

2.4 The effect of mass ratio on the probability of death in two-car crashes

2.4.1 Introduction

Crash speed is usually not included in routine reports because it is difficult to estimate. Thus if no comparisons of speed can be made, it might be thought that routine crash data can say nothing about the relationship between speed and probability of death. However, data on the relative numbers of driver deaths in the lighter and heavier of two vehicles that collide is sufficient to estimate the exponent if the relationship is a power function.

Some differences from the subject matter of Nilsson's model should be mentioned. Considering Nilsson's model, (a) this reflects both the occurrence of crashes and the occurrence of death given that a crash has occurred, (b) the speed referred to is mean or median travelling speed in Elvik et al. (2004), or speed limit in Nilsson (1982, p. 8), and (c) all road user types are included. Considering the data below, (a) this reflects only the occurrence of death given a crash (not the occurrence of crashes), (b) the speed referred to is to velocity change at impact, and (c) it applies to unrestrained vehicle occupants.

2.4.2 Data and theory

In two-vehicle crashes, the velocity change of the lighter vehicle is greater than that of the heavier vehicle. For any specific crash, the relative velocity of the vehicles, though not known, is the same for both drivers.

- Consequently, a comparison of injury severity of the driver of the lighter vehicle and of the driver of the heavier vehicle (at a given ratio of vehicle masses) gives some information about the dependence of probability of death on velocity change.
- Data on injury severity of passengers is difficult to use, as in most datasets the presence or absence of passengers is not recorded (unless they are injured).

The dataset analysed here is from routine police reports of road accidents in Great Britain, 1969-1972. There were no estimates of crash speeds in the data. Make and model of the cars involved were recorded, and thus the car masses obtained. Most vehicle occupants were unrestrained at that time. Data for head-on crashes, disaggregated according to whether the speed limit was at most 40 mile/h (i.e., urban areas) or was higher (i.e., rural areas), and by mass ratio, are given by Hutchinson (1977, Table 5; 1982, Table III). Intersection crash data in the form of counts are given as one-decimal percentages in Grime and

Hutchinson (1982, Tables 4a and 4b). For the methods of processing the data and some aspects of the results, see Grime and Hutchinson (1979, 1982).

Let R be the ratio of the mass of the lighter vehicle to the mass of the heavier vehicle, and v be the relative speed of the vehicles. In head-on crashes, the respective velocity changes are v/(1+R) and R.v/(1+R), and the ratio of these is R. (See also section 7.2.) For a given mass ratio, the ratio of the probabilities of death in the two vehicles is given in the data, and thus the exponent connecting these two ratios may easily be calculated. If, for example, a mass ratio of 2 led to the ratio of the probabilities of death being 8, then the exponent would be 3 (since 2 to the power 3 is 8).

Quite a popular way of analysing data is to plot the proportion of crashes in which the driver is killed against the ratio of the mass of the driver's vehicle to the mass of the other vehicle. A strong negative relationship is found, reflecting the greater velocity change in the lighter vehicle. However, there are two concerns about using this to study the relationship between velocity change and probability of death.

- Crashes occur at a wide range of speeds. Routine data from police reports aggregates all speeds. Any relationship evident in aggregated data may not be the true one.
- The dataset to be used here, as in the case of many others, excluded non-injury crashes. Probabilities of death are thus conditional on at least one of the drivers being injured.

An alternative method is to compare the drivers of the two vehicles in collision. Assume that the probability of death is a power function of velocity change, the exponent being c. Then the ratio of the number of drivers killed in the lighter vehicle to the number of drivers killed in the heavier vehicle is the ratio of $[v/(1+R)]^c.N$ to $[R.v/(1+R)]^c.N$ (where N is the total number of crashes, with damage-only crashes being included, and thus is not known). That ratio is R^{-c}, as the terms in v and N cancel out. Notice that the concerns of the previous paragraph do not apply.

Thus the power function assumption predicts that the ratio of the numbers of drivers killed in the lighter vehicle and in the heavier vehicle is R^{-c}. The dataset includes collisions at various values of R, and the exponent c is estimated by regression.

2.4.3 Results

Crashes in which R was at least 0.6 will be considered. These are largely car-car crashes. At more extreme mass ratios, the crashes are mostly car-truck crashes, and death of the truck driver is rare (and may be due to some unusual reason). For each of the four crash types, there were four data points, referring to R being in the ranges .60 to .69, .70 to .79, .80 to .89, and .90 to .99.

The following illustrates the reasoning. For head-on crashes, speed limit higher than 40 mile/h, mass ratio in the range 0.90 to 0.99, the numbers of fatalities were 65 (lighter vehicle) and 56 (heavier vehicle). The exponent c is estimated via $0.945^{-c} = 65/56$. The result is that c is found to be 2.6.

Of course, that is not the best method of estimating c because it uses so little of the data. If all 16 data points are included in a single regression, c is estimated to be 2.6 (standard error 0.4). It is a coincidence that the estimate is the same to one decimal place.

Some people may consider that crash speeds are so often inaccurate that it is a positive feature that this analysis has not used any such estimates.

For further results, see Appendix 3.

Another way of looking at this is to predict the ratio of fatalities from the suggestion of Moore (1970) that c about 3. If R is in the range .60 to .69, the ratio of fatalities will then be about $0.645^{-3} = 3.7$. The observed ratios were 73/29 = 2.5 (speed limit higher than 40 mile/h) and 54/12 = 4.5 (speed limit 40 mile/h or less). The prediction is reasonably accurate.

2.4.4 Serious injuries

This dataset also gives evidence about the effect of change of velocity on the probability of serious injury. I said earlier that this is proportionately considerably less than the effect on probability of death.

In the second paragraph of section 2.4.3, the ratio of numbers of deaths was 65/56, which is 1.16. The corresponding ratio of serious injuries (including deaths) was 758/711, which is 1.07. That is, there is a 7 per cent imbalance between the two vehicles, instead of a 16 per cent imbalance.

See Hutchinson (1976) for some evidence about how the probabilities of fatal and serious injury co-vary.

2.5 Kloeden et al. (1997)

Kloeden et al. (1997) compared the pre-crash speeds of cars involved in casualty crashes with the speeds of cars not involved in a crash. The speeds of the crash-involved cars tended to be higher.

That is a brief description of difficult work. The general strategy was that of a case-control study. Some further information about the methods is as follows.

- Relevant car drivers were sober, in a 60 km/h speed limit zone, in the Adelaide metropolitan area.
- The crash-involved cars (the "case" vehicles), 151 in number, were involved in crashes investigated in an in-depth at-scene study. Speed estimation was part of the crash reconstruction process.

- The non-involved cars (the "control" vehicles), 604 in number, were matched to the cases by location, direction of travel, time of day, and day of week. Speeds were measured with a laser gun.

Some further information about the results is as follows.

- Proportion of cars exceeding 60 km/h: 68 per cent of crash-involved cars, 42 per cent of the control vehicles.
- Proportion of cars exceeding 80 km/h: 14 per cent of crash-involved cars, less than 1 per cent of the control vehicles.

In summary, the risk of involvement in a casualty crash doubled with each 5 km/h increase in travelling speed above 60 km/h.

2.6 How good is the data?

I suspect that if the data (any of the data) were examined critically, it would be found that there were things wrong with it. That is, many inaccuracies and many biases are possible. Furthermore, the crash events differ between different categories of road user (e.g., car occupant, pedestrian, motorcyclist) and between different accidents. Thus evidence from car drivers (e.g., section 2.4) does not necessarily apply to pedestrians, for example.

Nevertheless, in my judgment the data is good enough to rely on.

- There is wide acceptance among road safety specialists that speed has a strong effect on the numbers of deaths and injuries. The topic has been studied by various different methods, employing various different meanings of speed (e.g., travelling speed, impact speed), and focussing on various types of crash.
- I even think that evidence about unrestrained car occupants largely applies to pedestrians, and vice versa. Both are killed by blunt injury, usually to the head or torso. The distances of deceleration whether by car interior or car exterior are a few centimetres.

There is a range of estimates of the effect of speed, and it is not surprising that this is so. A small selection of the evidence has been given. As far as this book is concerned, that variety does not matter. It is sufficient to understand that the effect of speed is big, and that therefore even quite a small reduction of speed will lead to a worthwhile reduction in deaths and injuries.

2.7 Slower speeds and the community

Personal experience, every day for many people, tells drivers in developed countries that modern car travel is very safe. Statistics of the number of deaths per billion journeys confirm that impression.

In contrast, as a community, we hate learning of the scores or hundreds of road deaths that occurred last year in our city or nation. So tragic, so unnecessary: someone should have driven a little slower.

Personal and community experiences are rather different. Our own walking, riding, and driving do not prepare us for the problem.

I hope this book will help you think more effectively about road safety, including about speeds and the place of speed management in the transport and transport safety plans of a city or nation. My opinion, I might say, is that in many cities what happens at intersections has a bigger influence on journey durations than does the speed of moving traffic: detailed attention to traffic signal settings and design of intersections can both reduce journey durations and improve safety.

3. From travelling to injury: Overview

3.1 Introduction

Section 3.2 specifies which I mean by typical or ordinary road accidents: at least one of the vehicles involved is travelling forward, and has a frontal collision with some sort of obstacle.

Section 3.3 describes what happens in typical pedestrian accidents, and section 3.4 describes what happens in typical car occupant accidents.

There are comments on injury occurrence and on medical treatment in sections 3.5 and 3.6, respectively.

3.2 Typical vs. unusual road accidents

This book is most relevant to what I will call typical or ordinary road accidents. I mean, those in which a car is moving forwards and collides with something.

I largely have in mind typical impacts, rather than typical accidents. The impact of one vehicle in a collision may be typical, and the impact of the other may be unusual. If, for example, a car strikes another car in the rear or in the side, the impact of the striking car is frontal (or approximately so) and typical, but the impact of the struck car is not.

The sequence of events in a typical road accident is as follows.

- The vehicle that we are principally talking about, vehicle A, is moving forwards.
- It collides with something. (This may be a stationary object, a moving vehicle, a pedestrian, etc.)
- If what it collides with is immovable (e.g., a much more massive vehicle, or a roadside tree), or has mass similar to that of vehicle A (as often in the case of another vehicle), vehicle A undergoes substantial acceleration (a deceleration) over a fraction of a second.
- There is no substantial intrusion into the occupant compartment of the vehicle.
- An unrestrained occupant continues moving forward and strikes the vehicle interior (e.g., the steering wheel) violently. An occupant restrained by a seat belt or air bag is decelerated more gradually.
- Injury to an occupant is caused by blunt impact. Most life-threatening injuries are to the head or the torso.
- Alternatively, injury is caused by blunt impact to a pedestrian. Many impacts to pedal cyclists and some to motorcyclists are likely to be similar to pedestrian impacts.
- There is no further event that causes injury --- there is no further impact, for example.

Examples of typical road accidents are as follows.

1. A car, moving forwards, strikes a pedestrian's legs. The pedestrian rotates and his or her head strikes the car's bonnet or windscreen. The speed of the head impact is approximately that of the car when striking the pedestrian's legs. The impact between the head and the car surface is not likely to be normal (perpendicular), and so the normal component of the velocity is rather less than that of the car.
2. Frontal impact of the car. After the first moment of impact, an unrestrained car occupant continues moving forward, he or she strikes the steering wheel or other part of the vehicle interior, and the relative velocity at impact is approximately the vehicle's change of velocity.
3. Similar to the previous type, except the car occupant is restrained by a seat belt, air bag, or other device.

See chapter 8 for how a seat belt works in a typical frontal impact. Another great advantage of a seat belt is that it greatly reduces the likelihood of being ejected from the vehicle.

I am not chiefly thinking of crashes that are initiated by loss of control or loss of stability. Undoubtedly there is theory relevant to tyre-road adhesion, overturning because of "tripping", overturning of vehicles with a high centre of gravity, and stability of two-wheeled vehicles. These topics would very likely appear in a more wide-ranging book. I omit them as I do not regard the accidents as "typical". However, in many loss-of-control crashes there is a fairly typical frontal impact.

Quite a number of other road accidents are sufficiently similar to the above types that much of this book will be relevant to them.

- Multi-vehicle accidents can sometimes be regarded as several two-vehicle accidents, for example.
- The book may be relevant even to many accidents classified as overturning: it is common for a quarter-turn of a vehicle on to its side to be recorded as overturning in accident data, and this may be an unimportant aspect of the accident.

In the examples of typical road accidents, a "car" was referred to, rather than a "vehicle". Some of this book is relevant to some accidents to trucks, buses, motorcycles, and pedal cycles, but many accidents to these vehicles are not typical in the present sense.

An important category, numerically, of road accidents that are not "typical" in the present sense is rear impacts of a car with a car, including those in which the lead vehicle is stationary.

- For the striking vehicle, the impact is frontal, and this is what I am calling a typical or ordinary impact.
- The relative velocity of the vehicles is usually low.
- Occupants of the struck car are protected by the seat backs.
- See section 7.3 for some comments on this type of crash.

Examples of exceptional or atypical road accidents are listed below. These examples serve to emphasise the variety of events that can happen. Some are quite common, others are rare.

1. Side impact (in the case of the vehicle that is struck).
2. Rear impact (in the case of the vehicle that is struck).
3. Glancing impacts (I am thinking of vehicles hitting a roadside barrier and sliding along it).
4. Overturning.
5. Intrusion into the passenger compartment of the vehicle.
6. Ejection of occupant from vehicle following impact.
7. Occupant falls out of a vehicle.
8. Wheels of a vehicle run over the head or body of a pedestrian or other road user. Also, the wheels of a vehicle running over the feet of a pedestrian. (This may not often be life-threatening, but broken bones of the feet are serious.)
9. In many truck-car accidents, the truck is so much more massive than the car that the change of velocity of the truck is small.
10. The vehicle is not moving forward.
11. A short-duration impact is not the chief event. For example, fire, immersion in water, crushing, fall from a cliff.
12. Ones in which the injury is from a pointed or penetrating object, or a projectile.
13. More than one impact. There may be three or more vehicles, for example.
14. Due to illness of the driver, failure of the vehicle (e.g., tyre or brake failure), or failure of road or road equipment.
15. Ones involving grossly irresponsible driving. This may include vehicles that are being pursued by police.
16. Ones involving grossly irresponsible pedestrian behaviour (e.g., lying in the road).
17. Ones that are deliberate. (In this case, accident is the wrong word, of course.) This includes suicide, some acts resembling suicide, murder, some forms of manslaughter, similar impacts in which death was intended but did not occur, similar impacts which were deliberate but not intended to cause death, and so on.

Many accidents caused by alcohol or drugs or fatigue are typical in the sense that I mean, even if some aspects are unusual. There may be quantitative effects of these factors: a different driving speed, poorer perception, slower reaction, poorer decision-making, and so on. I will not, however, comment on the exact mechanisms by which increased risk occurs.

Most of the exceptional types just listed may be included in a road accident dataset, but some may be excluded from some types of dataset.

This is a convenient point to note that in most jurisdictions, most knowledge about road accidents comes from data collected by the police, and passed on by them to local and national government. Some knowledge about road accidents comes from databases collected by hospitals on their patients (especially their in-patients), and by the death registration authorities about causes of death. Some knowledge about road accidents comes from databases collected by insurance companies, workplace health authorities, and so on.

3.3 Typical pedestrian accidents

There are differences between injury to pedestrians and injury to car occupants. The pedestrian case is perhaps the simpler, so will be discussed first. The sequences of events are given in text, and are also shown in Figures 3.1 and 3.2. Perception of danger and reaction to it is not discussed at this point, but will begin in section 5.3; the initiation or causation of the emergency is largely outside the scope of this book, as was noted in section 1.1, but there will be some comments in chapter 4.

Vehicles that drive themselves or that act autonomously in some circumstances (e.g., in an emergency) are currently prominent in the news. Thus I have below used wording such as "If the driver, or the car, realises the danger".

For pedestrian accidents, the sequence of events, in idealised form, is as follows.

1. **Travelling.** The car is travelling forwards (speed = v).

2. **Braking.** If the driver, or the car, realises the danger of an imminent collision with the pedestrian, the car may brake (deceleration = a). This does not always occur.

3. **Leg and hip impact.** The car strikes the pedestrian's legs (speed = u, which will be smaller than v if there has been braking).

4. **Human movement.** The pedestrian rotates and the car (usually the bonnet or windscreen) strikes the pedestrian's head. The speed is typically approximately equal to u, though this is not usually at a right angle to the car surface.

5. **Head impact.** Over a period of a few milliseconds, there is substantial acceleration of the pedestrian's head, that may cause serious injury or death. Impacts and injuries of the body and limbs are common, also.

6. **Injury.** Within a second or so of impact, the pedestrian's immediate injury has occurred.

7. **Treatment and outcome.** If death has not occurred, there will be medical treatment and rehabilitation; there may be medical complications; the pedestrian may die, or may survive with long-term major disablement, minor disablement, or normal health.

1. Travelling, speed = v

↓

2. Braking, deceleration = a

↓

3. Leg and hip impact, car strikes pedestrian's legs at speed = u

↓

4. Human movement, pedestrian rotates, impact between car and head at speed approximately u

↓

5. Head impact, lasting a few milliseconds

↓

6. Injury to skull and brain within a second or so of impact

↓

7. Treatment and outcome, possibly death

Figure 3.1. Summary of the sequence of events in a typical pedestrian accident. Here and in Figure 3.2, a downward arrow means "is followed by".

3.4 Typical car occupant accidents

The sequence of events, in idealised form, is as follows.

1. **Travelling.** The car is travelling forwards (speed = v).

2. **Braking.** If the driver, or the car, realises the danger of an imminent collision, the car may brake (deceleration = a). This does not always occur.

3. **Vehicle impact.** With speed u (which will be smaller than v if there has been braking), the car strikes an obstacle directly in front of it, which may be a moving vehicle. The car undergoes substantial change of velocity in a small fraction of a second. The impact may be normal (perpendicular) to an obstacle that is stationary and immovable, in which case the change of velocity equals u. Alternatively, the movement of the car and the obstacle (possibly another vehicle) may be

calculated on the basis of conservation of momentum in an inelastic collision. The calculations include the car's change of velocity. If the impact is approximately frontal but not with an immovable object, it is typically considered as a frontal impact with an immovable object, but at an impact speed equal to the car's change of velocity. Human movement (4U or 4R below) is modified accordingly.

4U. **Human movement (unrestrained).** As the car stops or changes velocity, an unrestrained occupant of the car continues moving, and strikes the interior of the car. The car's own impact has usually finished by this time and the car has attained its post-impact velocity. This might be zero, as with a normal impact with an immovable object, in which case at impact the relative velocity of the human and the car interior is approximately u.

4R. **Human movement (restrained).** A restrained occupant of the car will be decelerated by the seatbelt, airbag, or other restraint, and either does not strike the car interior or strikes it with reduced relative velocity. A very stiff restraint may itself cause injury --- this does not necessarily indicate some failure of the restraint, as it is likely that the injury would be more severe in the absence of the restraint.

5. **Human impact.** Over a period of a few milliseconds, there is substantial acceleration of the car occupant, that may cause serious injury or death; head and torso injuries are the ones most likely to cause death.

6. **Injury.** Within a second or so of impact, the car occupant's immediate injury has occurred.

7. **Treatment and outcome.** If death has not occurred, there will be medical treatment and rehabilitation; there may be medical complications; the car occupant may die, or may survive with long-term major disablement, minor disablement, or normal health.

Simple modelling of the impact of two vehicles (step 3 above) will be discussed in Chapter 7. Simple modelling of the movement of the occupants relative to the vehicle (step 4 above) will be discussed in Chapter 8.

3.5 Comment on injury occurrence

Injury occurs when the pedestrian or car occupant strikes something stiff. The component of the relative velocity normal to the stiff surface will be important in determining the severity of injury. The most important other factors are likely to be characteristics of the surface (such as its stiffness), and characteristics of the human (such as the effective mass, which part of the human is impacted, and frailty).

1. Travelling, speed = v

↓

2. Braking, deceleration = a

↓

3. Vehicle impact, car strikes something at speed = u, and undergoes substantial change of velocity in a small fraction of a second

↓

4. Human movement
   - 4U. As the car stops or changes velocity, an unrestrained occupant of the car continues moving, and strikes the interior of the car
   - 4R. Alternatively, a restrained occupant will be decelerated by the seatbelt, airbag, or other restraint, and either does not strike the car interior or strikes it with reduced relative velocity

↓

5. Human impact, lasting a few milliseconds; head and torso injuries are the ones most likely to cause death

↓

6. Injury within a second or so of impact

↓

7. Treatment and outcome, possibly death

Figure 3.2. Summary of the sequence of events in a typical car occupant accident.

A couple of points should be made about frailty.

- In part, this means whether bones are likely to break and soft tissues are likely to tear (what might be called fragility). But it is often used in a broader sense, to mean whether a poor outcome (e.g., death, permanent disablement, long stay in hospital) is likely from a given impact.
- It is likely to be much easier for a crash test dummy or pedestrian headform to be similar to a human in respect of mass than in respect of frailty. An important characteristic of an impact to a human head may be the acceleration. This is determined, in part, by the effective mass of the

head, and the mass of a headform can be specified. Frailty is relevant at a later stage: given the acceleration, does the skull fracture, is the brain injured, how long does the person spend in hospital --- the answers to these questions will reflect frailty in one or other sense.

High speed of travel is likely to lead to high speed of the vehicle at impact, which is likely to lead to high speed of the impact of the human (especially the head), which is likely to be very dangerous, and the result is likely to be that a high proportion of people are seriously or fatally injured. Can the reasoning be reversed? That is, should empirical evidence of a high proportion of people seriously injured be interpreted as evidence of high speed (high average speed of impact, that is)? It is suggestive of high speed, yes, but other possibilities need to be considered. High frailty and high stiffness are alternatives. Poor medical treatment, possibly. It is often possible to argue about how severe an injury is, so a poor definition of injury severity is another alternative. In many situations, high speed will be much the most plausible of the possible reasons.

3.6 Comment on medical treatment

Step 7 (sections 3.3 and 3.4) could be split into several steps --- for example, as below.

7. **Treatment and outcome.**
7.1 First person on scene.
7.2 First competent treatment at the crash scene.
7.3 Treatment at the hospital emergency department.
7.4 Treatment as a hospital in-patient.
7.5 Rehabilitation.

Most aspects of this are outside the province of the specialist in road safety. Nevertheless, it seems likely that improvement has taken place at many stages of treatment, and has contributed to the reduction in road deaths that has occurred in developed countries since the 1970's.

Aspects of step 7 that are likely to be of interest to the specialist in road safety include the following.

- Classification of the injury severity as serious or slight.
- Classification of the outcome as fatal or non-fatal. For police data, most jurisdictions have a rule that deaths within 30 days are classified as road accident deaths, and later deaths are not.
- The operation of the emergency services, particularly because some vehicles these days are capable of detecting that they have sustained an impact and signalling this to the emergency services.
- Data from hospitals on the nature and severity of injury. In these respects, hospital datasets are typically better than police data.
- A proportion (quite a small one) of those seriously injured are at real risk of dying, even with good medical treatment. It would be a considerable benefit to the study of road safety if these cases were identifiable in datasets.

- Data on the long-term consequences (health and other) of being injured, particularly because of the economic and social implications and therefore the valuation of prevention and mitigation.

4. Types of crash, reasons for an obstacle, and reasons for mistakes

4.1 Introduction

Many road accidents are typical, or ordinary. By this, I mean that at least one of the vehicles involved is travelling forward, and has a frontal collision with some sort of obstacle. Possible things that might be struck include an object, or a person, or a vehicle. Chapters 5 and 6 of this book are about the reaction of an autonomous vehicle, or a human driver, when faced with an obstacle. It is natural to ask three questions, as follows.

1. As well as collisions with obstacles, what other types of road crashes are there?
2. Why was the obstacle present?
3. If the obstacle was present deliberately and consequent upon some mistake, why was the mistake made? This refers to the well-known topic of gap acceptance. A vehicle driver or pedestrian, for example, has accepted a gap in the traffic stream that has turned out to be unsafe.

These questions will be discussed in sections 4.2 - 4.4. It would be natural to follow up question 1 by asking what are the relative frequencies of the several types of road crash. But perhaps that is too difficult a question. It would be natural to follow up questions 2 and 3 by considering whether, given that we know reasons why an obstacle may be present, we can prevent that happening. But perhaps that also is too difficult or broad a question to deal with. An overview of the proposed methods of classifying crashes and the reasons for them will be given in section 4.5 as Figure 4.1.

You may feel, at the end of this chapter, that not very much has been achieved. But chapters 5 and 6 will be about a very late stage in the events of a subset of accidents (what I am calling the typical ones). It is natural to want to consider earlier stages in those accidents, and consider also other types of accident. I am unable to do that satisfactorily at present, but this chapter is attempting to lay the groundwork for that.

4.2 As well as collisions with obstacles, what other types of road crashes are there?

In a typical road accident, the vehicle that we are principally talking about is moving forwards, and it collides with something. (This may be a stationary object, a moving vehicle, a pedestrian, etc.) This is listed first in the list below, followed by some examples of other types.

- Impact with some obstacle.
- Overturning.
- Occupant falls out of a vehicle.
- Wheels of a vehicle run over the head or body of a pedestrian or other road user. Also, the wheels of a vehicle running over the feet of a pedestrian.

(This may not often be life-threatening, but broken bones of the feet are serious.)

- The vehicle is not moving forward.
- A short-duration impact is not the chief event. For example, fire, immersion in water, crushing, fall from a cliff.

I think overturning is much less frequent than impact with an obstacle, but is much more frequent than the other accident types listed.

In some datasets, a record of overturning having occurred would not necessarily indicate that overturning was the first event, or was an important or injury-causing event; for example, a quarter-turn of a car on to its side subsequent to a collision might be recorded as overturning, and might not be important.

It will often be desirable to use a classification that applies to a given vehicle in the impact. This would mean "impact with obstacle" category would be subdivided.

- Impacts with pedestrians and other vulnerable road users are obviously different from impacts with roadside objects or with other vehicles.
- In rear impacts, the striking vehicle has a frontal impact and the struck vehicle has a rear impact.
- In side impacts, the striking vehicle has a frontal impact and the struck vehicle has a side impact.
- It may be desirable to distinguish vehicles for which there is intrusion into the occupant compartment from those for which there is not.

4.3 Why was the obstacle present?

Below is a list of four possible reasons why the obstacle was present. The first is the usual reason, and will be discussed in section 4.4. In what follows, the "host vehicle" refers to the vehicle that has an AEB system, or a human driver, that reacts to the obstacle.

- The obstacle is present deliberately, but as the result of a mistake.
- The obstacle is there deliberately and perhaps without any mistake, but in some sense has become stuck. Such an obstacle is likely to be present for at least some seconds, and may be avoidable.
- The obstacle is there deliberately and has a right to be there. For example, the host vehicle may lose control and strike something (an object or a vehicle on or off the road), or may run into the back of the vehicle ahead.
- The obstacle's presence is inadvertent, or occurs for a reason that cannot be considered a normal mistake. For a list of reasons, see the next paragraph.

Included in the fourth item in the foregoing list are a number of different reasons for initiation of the accident.

- The obstacle is a vehicle that is out of control, but is otherwise being driven normally.
- Due to illness of the driver, failure of the vehicle (e.g., tyre or brake failure), or failure of road or road equipment.

- Grossly irresponsible driving. This may include vehicles that are being pursued by police.
- Grossly irresponsible pedestrian behaviour (e.g., lying in the road).
- Some actions that are deliberate. (In this case, accident would be the wrong word for the event, of course.) This includes suicide, some acts resembling suicide, murder, some forms of manslaughter, similar impacts in which death was intended but did not occur, similar impacts which were deliberate but not intended to cause death, and so on.

Some of these events (in particular, illness of the driver, suicide, and murder) may not be included within the definition of a road accident.

4.4 If the obstacle was present deliberately and consequent upon some mistake, why was the mistake made?

As noted in section 4.3, probably the most frequent reason for an obstacle being present is that it is there deliberately, albeit as the result of some sort of mistake. The individual (pedestrian, driver, or rider) may have perceived a gap in the stream of traffic, and accepted that gap, in the sense of attempting to join the traffic stream, cross the traffic stream, or use that lane of the road to overtake.

Gap acceptance is a topic often found in textbooks. Among the well-known factors relevant to good performance of the task are the following.

- Clear lines of sight;
- Normal eyesight, normal decision-making ability, normal motivation, and normal ability to move;
- Perception of vehicles' speeds;
- Perception of gaps between vehicles;
- Expectations about vehicle speeds and the gaps between vehicles are likely to be important, too;
- In many cases, being able to assess gaps and speeds for two or more traffic streams simultaneously;
- Not being so impatient as to act on poor visual information;
- Being aware not only of what is seen but also of what may potentially be present but cannot be seen (blind spots).

The human aspects of these might be classified as attentional, sensory, judgment, decision-making, execution, and so on.

As far as I know, theories of human error in gap acceptance have not yet become popular. I can imagine some reasons. (a) Some people appear to tolerate a very narrow margin of safety --- the distinction between a successful and an unsuccessful action may be tiny. (b) Routine accident data is not well-suited to studying the problem. (c) There may be no way of identifying the different types of error that the theory may propose (no way in any imaginable accident data, that is). (d) It is difficult to conduct experiments (e.g., using a driving simulator or virtual reality). (e) It is tempting to instead do something immediate and practical about road safety.

I can suggest how to begin classifying human error.

- Be clear what type of crash is under discussion. The natural type of accident to give as an example is an obstacle (pedestrian or vehicle) moving into the path of a vehicle.
- For this example, distinguish between the following. (a) Error by the person without right of way. (b) Error by the person with right of way. (c) Misunderstanding about who has right of way.
- Restrict attention to short-lasting actions (and consider separately relatively long-lasting states such as speeding).
- Classify actions in three ways: the person is taking the initiative, or is reacting; the action is normal, or is unexpected (an act that is intended to promote safety may be dangerous if it is unexpected); and according to how much thought precedes them. As to thought, approximately 1 second might be time for a reaction but not for a thought, 2 seconds might be time for a thought and a decision, 10 seconds might be time for thoughts and perhaps planning.
- Distinguish between (a) errors of omission, and (b) errors of commission.
- A psychological classification of errors, similar to that at the end of the second paragraph of this section, is also likely to be useful.

I should note that certain safety-related quantities that are probably available to the human visual system may be relevant to the decisions of both the person who accepts a gap (and perhaps creates an emergency) and of the driver who reacts to the emergency. See Hutchinson (2018a, section 11.5), Lee (1976), and Stewart et al. (1993). These might be components of some future account of gap acceptance and human error.

4.5 *Discussion*

Several questions were raised in section 4.1. This chapter has attempted some response to them. The main line of discussion has been in two parts.

- Selection of collisions with obstacles for which the obstacle was present deliberately and consequent upon some mistake (sections 4.2 and 4.3).
- Classification of the mistake in several ways (section 4.4).

See Figure 4.1 for a summary. For types of crash and types of reason not selected, it is likely that other methods of subclassification are possible and desirable, but that has not been followed up here.

This method of selection and classification has been proposed because I would like to know more about what came before the emergency, and what generated it. Although experts have classified human errors and have produced theories about human error, I cannot see that these are useful concerning errors on the road.

The method has not been tested or used. The suggestions are very tentative. It might be said that I have got things the wrong way round: a human mistake comes before an accident, therefore classification of mistakes should come before consideration of type of crash. My response is that we are not yet at that stage. Selecting a type of crash helps us devise a system of classification of error.

It would be difficult or impossible to use routine crash data from the police to say why an obstacle was present, and why a mistake was made: administrative systems of data collection can be accurate in respect of facts, but are poor in respect of more difficult or subjective matters. In practical use and for practical reasons, classification of road accidents is different from that discussed here.

As discussed in section 3.2, there are several types of road crash.		
↓		↓
Collisions with obstacles. There are several physical types of these, as mentioned in the final paragraph of section 4.2.		Various other types: see first paragraph of section 4.2.
↓		
For collisions with obstacles, ask why the obstacle was present.		
↓	↓	
Deliberately and consequent upon some mistake.	Various other reasons: see first paragraph of section 4.3	
↓		
For these, classify the mistake in several ways. (1) Whether the mistake was made by the person without right of way, or the person with right of way, or there was misunderstanding about who had right of way. (2) The action is an initiative or a reaction. (3) The action is normal or unexpected. (4) According to how much thought there was. (5) Whether it was an error of omission or commission. (6) Attentional, sensory, judgment, decision-making, execution errors: it is likely that the factors listed in the second paragraph of section 4.4 can be categorised in this way.		

Figure 4.1. Summary of a method of classifying crashes and mistakes. Here, a downward arrow simply leads from one sentence to one or more others.

5. A model for the reaction of a driver or an autonomous system

5.1 Introduction

A model will be given in section 5.3 for what happens to a vehicle --- controlled by a driver or by an autonomous system --- when it encounters an obstacle. The model is a very simple one, but (so I hope) nevertheless useful. It involves the vehicle decelerating at a constant rate (a constant rate of change of velocity, that is). As preparation for section 5.3, section 5.2 states one of the well-known equations that are true for motion with constant acceleration.

Section 5.4 gives an equation for the impact speed, that is, the speed with which the vehicle strikes the obstacle. If the vehicle does not brake at all, the impact speed is unchanged from its travelling speed v. If the vehicle brakes sufficiently early and strongly, it does not hit the obstacle, in which case the impact speed is given as zero.

Section 5.5 offers some comments directly on the model or hypothesis for reaction and braking, and section 5.6 is wider discussion.

5.2 The effect of constant deceleration

The vehicle's impact speed has a closer connexion with human injury than travelling speed does. It will therefore be useful to have an equation for impact speed u in terms of travelling speed v. This equation will also involve deceleration a, and distance s between where the speed was v and where the speed is u.

Consider a vehicle initially travelling at speed v, that starts braking with constant deceleration a when it is at a distance s from an obstacle. (The obstacle is presumed to be stationary or moving across the path of the vehicle, but not moving towards or away from the vehicle.) If the vehicle fails to stop before hitting the obstacle, the speed of impact u will satisfy

$$u^2 = v^2 - 2.a.s,$$

that is,

$$u = (v^2 - 2.a.s)^{0.5}$$

This type of equation --- referring to motion with constant acceleration a --- is typically encountered at school under some such name as Newton's equations of motion, or the SUVAT equations. See Appendix 4 for a few more words on this. One possible source of confusion should be mentioned.

> In the present notation, u is the second (lower) speed, v is the first (higher) speed, and a is considered positive even though it is a deceleration. This is different from the notation typically encountered in physics textbooks.

To allow for the possibility that the vehicle may stop before hitting the obstacle, and to represent this as an impact of zero velocity, the equation should instead be written as

$u^2 = \max\{0, v^2 - 2.a.s\}$

5.3 What the vehicle might do in an emergency: Model [A]

Suppose we have a model, or know the rule, for how the vehicle behaves when it encounters an obstacle. We may then be able to work out whether the vehicle strikes the obstacle, and if so, at what speed. The rule might apply to a conventional vehicle controlled by a driver, to a vehicle equipped with autonomous emergency braking, or to an autonomous vehicle.

I will consider the rule below, which I will label model [A]. A similar model is in Hutchinson (2015).

> [A] The vehicle is travelling at speed v. If there is an obstacle directly ahead and within a distance d, then emergency braking with deceleration a will begin after time t.

It may be appropriate to refer to d as the range of the sensing system, and to t as a reaction time. The intended context is that of a vehicle that is not following another vehicle. I say this because I want situations such as dashing out of a pedestrian to be handled. Nevertheless, obstacle-detection-decision-reaction is a similar sequence whether or not the situation is one of vehicle following. Model [A] might be called a delayed constant acceleration model (Markkula et al., 2012, especially pp. 1123-1125). Section 6.3 will suggest some building blocks from which better models might be constructed. More complicated models have been considered seriously for some years by the experts (Brännström et al., 2010).

The testing of Autonomous Emergency Braking (AEB) systems is currently of great interest. Research on drivers' reactions to emergencies has not been as popular as might have been expected, and I do not know of any comparisons of the data with something similar to model [A]. Thus while model [A] might apply to a driver or to an AEB system, I will concentrate on AEB systems.

It is likely that emergency deceleration a will be regarded as a property of the braking system, tyres, and road surface, rather than of the AEB system, and that standard methods will be used to estimate it.

It may be possible --- by plugging into the vehicle's electronics, for example --- to determine the exact moment at which it first becomes true that "there is an obstacle directly ahead and within distance d", and the exact moment at which deceleration a begins. That would help in estimating t and d. This suggests that the test should involve a sudden challenge to the vehicle rather than, for example, the vehicle being driven towards a continuously-viewed stationary obstacle. For this, see Hutchinson (2018a, especially chapter 7.) It is likely that deceleration a and impact speed would in these circumstances be viewed as outside the scope of the experiment.

Note also that there may be a distinction between the moment when the AEB system commands emergency braking, and the moment when deceleration a begins: the wording of the model being used for data analysis will need to be adjusted to the method of testing employed.

Use of a sudden challenge and accessing the vehicle's internal communications seem to be not very popular at present. What will be considered instead will be testing of whether impact occurs, and (if so) at what speed.

5.4 Implications of model [A] for impact speed

The impact speed u can now be obtained. Let x be the original distance of the obstacle. During the time t, the vehicle will move a distance v.t. The time t will start elapsing when the vehicle is at distance min{x, d} from the obstacle. The vehicle will thus be at a distance min{x, d} - v.t when braking commences. The square of the impact speed will be

$u^2 = v^2 - 2.a.(\min\{x, d\} - v.t)$

Example. Suppose that v = 17 m/sec (which is 61.2 km/h), a = 8 m/sec/sec, x = 25 m, d = 30 m, and t = 0.5 sec.

- Then $u^2 = 17^2 - 2 \times 8 \times (25 - 17 \times 0.5)$, and thus impact speed u is 5 m/sec.
- Furthermore, the effects of changes in the conditions can easily be worked out. If v is reduced to 16 m/sec, impact is avoided; if a is reduced to 7 m/sec, u increases to 7.6 m/sec; if x is reduced to 10 m, u increases to 16.3 m/sec; if d is reduced to 10 m, u increases to 16.3 m/sec; if t is reduced to 0.3 sec, impact is avoided.

Similar calculations in chapter 13 of Hutchinson (2018a) make me feel that impact speed will often be reduced. As the percentage reduction in fatalities is likely to be a multiple of the percentage reduction in impact speed (see chapter 2), I think it likely that AEB will be very effective in reducing deaths.

The above equation is only valid if there is some braking but not enough to prevent impact. We may wish to explicitly allow for the other possibilities.

- The first is that the vehicle is travelling sufficiently fast that no braking occurs before it hits the obstacle. This means that u^2 will equal v^2 if min{x, d} is less than v.t.
- The second is that the vehicle is travelling sufficiently slowly that it stops before hitting the obstacle. This means that u^2 will equal 0 if v^2 is less than 2.a.(min{x, d} - v.t).

Allowing for these cases, the equation will be

$u^2 = \max\{0, v^2 - 2.a.\max\{0, \min\{x, d\} - v.t\}\}.$

5.5 Comments on model [A]

Several comments about [A] may be offered.

- It refers to a moment very late in the emergency, when very strong braking is undoubtedly needed.
- The action taken is very simple --- very strong braking.
- The condition for that action is very simple --- being within a distance d of an obstacle.
- The range d and the reaction time t are the only characteristics of the autonomous system. (Deceleration a is a third characteristic of the vehicle; it may be convenient to consider a separately from d and t because it may be estimated by traditional methods.)
- The measure of the performance or degree of success is the impact speed u. (As this depends on a as well as on d and t, and it is likely that a is appropriately regarded as a characteristic of the braking system and tyres rather than of the autonomous system, u is not a measure of the success of the autonomous system alone.)
- There is no attempt to describe the mechanism of perception of the danger, processing of the information, decision-making, and taking action. There is no attempt, for example, to model any tracking of the position (relative to the vehicle concerned) of a pedestrian or another vehicle. Clearly, therefore, there is no attempt to model how actual operation compares with ideal operation, that is, to model anything that might be described as failure of operation.
- It is likely there is a sensing system on the vehicle, and a decision-making unit, but not a transmitter. There are alternatives, however. Pedestrians and vehicles might carry transmitters, with the signals being detected and fed into the decision-making unit. Or signals from many road users might be processed by infrastructure (either at the roadside or at a distance), appropriate actions computed, and instructions sent to the braking systems of vehicles.
- Model [A] is clearly expressed.

There is potential danger of loss of control from braking strongly and suddenly, and potential danger also from operating a vehicle in a manner that is not smooth and predictable. I feel, however, that these dangers are uncertain and vague compared with the real and obvious danger of not reacting quickly and strongly enough.

The equations given are not designed for, or adapted to, any specific method of testing a vehicle or driver. Using them with a specific method may be difficult. With the equations as they are, the difficulty may lie in knowing what distance x is.

5.6 Discussion

My opinion is that emergency braking is the most important thing that the vehicle might do.

- I feel that in most circumstances the driver will be too slow to react, and the effect of a warning is likely to be minor. However, not everyone is pessimistic about the effectiveness of a warning (e.g., Lubbe and Kullgren, 2015). I do think a warning system might be effective in heavy traffic. Firstly, drivers might follow at longer distances (in order to avoid triggering the warning). Secondly, drivers may be quick to react, as the context is unambiguous.
- Priming the braking system (so that when braking is commanded, reaction will be quicker than otherwise) is perhaps useful.
- Weak braking is perhaps useful.
- As will be mentioned in section 6.4, other researchers have included autonomous steering as a possible response by a vehicle.

To achieve a substantial reduction in fatalities and serious injuries, AEB systems must intervene decisively and must have some effect at reasonably high speeds such as 50 km/h and over. I do not deny that there are additional uses for systems to avoid and mitigate collisions, including the avoidance of minor low-speed impacts in urban traffic. Weak braking would have the advantage that occasional false positive weak braking might be accepted by drivers; if early enough, it might slow the vehicle by a useful amount in a true emergency.

A specific matter of practical importance is that it is possible to treat road surfaces so that skid resistance becomes greater --- that is, the coefficient of friction becomes greater. As the coefficient of friction is important in determining the speed reduction before impact (see section 5.4), it should be the case that a greater coefficient of friction leads to some accidents being avoided, and the impact speeds of others being reduced. However, a lot of people are of the opinion that rear end accidents become more common when such road surface treatments are applied at traffic light approaches. Careful analysis of empirical road accident data is needed. Ideally, there should also be careful theoretical analysis of what might happen to a succession of vehicles if the first one brakes very strongly.

6. Variations of the model

6.1 Introduction

I imagine that many readers have noticed the simplicity of model [A] in section 5.3, have thought that real AEB systems do not work quite like that and drivers faced with an emergency do not react quite like that either, and have realised there needs to be something better. But at that point there may be a block. Improve model [A], yes. But it is not clear how to do that.

The purpose of this chapter is to suggest some building blocks from which better models can be constructed. (See also Hutchinson, 2016, and chapter 12 of Hutchinson, 2018a.) There is always likely to be a contrast between simple models that are easy to use but unrealistic, and complicated models that are more realistic but difficult to understand and use. Very likely, different applications will require different models.

6.2 General style of modelling

The correctness of the specifics of model [A] might be questioned, but it is hoped that at least the general style of the analysis will be useful. AEB is likely to save lives, and it is important that as much benefit is gained as soon as possible. Using this type of analysis, it is possible to understand AEB performance and extrapolate to conditions not directly tested. The style of analysis referred to is based on a model that is expressed sufficiently clearly that equations can be derived.

The following are suggested as important.

- A concise verbal description, perhaps a single sentence.
- The model will include a set of characteristics of the AEB system and vehicle, analogous to d, t, and a in model [A].
- The model will also refer to input variables describing the conditions of the crash or the test, such as x and v.
- There will be desired output variables, such as impact speed. Whether or not an impact occurred is a simple output. Some methods of testing may give the time from challenge until the AEB system commands emergency braking, or the distance available for braking.
- There will be equations to calculate the outputs from (a) the inputs, and (b) the AEB characteristics.
- The input and output variables will have some implications for the general strategy of testing chosen, such as whether it needs to utilise the vehicle's electronics or should only use measurements available outside the vehicle, and whether the aim is to test the AEB system alone or the whole vehicle including brakes and tyres.

A summary measure of performance referring to a realistic population of crashes, rather than a single crash in particular test conditions, is desirable at a later stage. This would be obtained from calculations that start from the value of an output variable observed in the test conditions, and the values of the input variables observed in real crashes. For this idea, see chapter 11 of this book.

6.3 States of vehicle, rules for transition, and desired output

Hutchinson (2016) suggested that many different models of reacting to an emergency could be constructed from the following components.

- A small number of states of the vehicle (e.g., normal driving, braking, stationary).
- Rules for transitioning between states. The rules will include one or more parameters that are characteristic of the driver or vehicle.
- A desired output or dependent variable (e.g., impact speed).

In model [A] of section 5.3, there are three states: travelling normally, emergency deceleration, and end. Transition from travelling normally to emergency braking occurs at a time t after a simple condition is satisfied, namely, "if there is an obstacle directly ahead and within a distance d".

It was said in section 5.3 that the context for model [A] is a vehicle that is not following another. Model [A] might apply also to a vehicle that is following another, but the distance d and time t might be different. More likely, strength of braking might depend on distance from the vehicle ahead, relative speed of the vehicle ahead and the host vehicle, and relative acceleration of the vehicle ahead and the host vehicle.

In other models, there might be further states and more complex transition rules. The rules might be subject to conditions involving many variables. The list in Table 5 of Hutchinson (2016) includes travelling speed, precise positioning of the obstacle, movement of the obstacle, history of the obstacle, acceleration of the obstacle, source of the information, steering wheel position, braking and steering wheel movement, the driver's foot, and environmental conditions and obstacle characteristics. Perhaps the conditions should also have included a computation at every moment of whether it were possible to avoid the obstacle by some action of the driver, the implication being that if that were possible, the system should not intervene. The possible driver actions would be to brake, to accelerate, to steer left, to steer right, or more than one of these (Brännström et al., 2010).

The transition rules might be probabilistic rather than deterministic. If, for example, operation of the system is not as good as ideal operation, probabilistic rules might be a way of modelling this. In the context of the human driver, the review by Dilich et al. (2002) places a lot of emphasis on the variability of reaction when confronted with something outside the range of normal driving experience.

It is likely that an autonomous system will be able quite easily to classify the general traffic and driving situation. For example, the vehicle might be stationary, accelerating, cruising (not following), following, decelerating, or braking. (Such categories were employed by Khaisongkram et al., 2011.) Speed limit and driver's desired speed may be available to the system. The set of rules that the system follows in an emergency might be different for the different categories of traffic and driving situation.

Words like "perception" and "understanding" usually apply to a human. Nevertheless, they might be applied to an autonomous vehicle. The issue does not arise in the case of model [A], which describes a very limited situation: it is not necessary to write that the AEB sensor perceives an obstacle in the path of the vehicle, and the AEB central processor understands that a collision will occur. But what if there is much more complexity, as in the case of an autonomous vehicle? Zhao et al. (2017) have argued that a knowledge representation method is needed. This enables perception of driving environments (the outputs of the sensor systems) to be transformed into understanding of driving environments. Understanding facilitates correct decision-making.

6.4 Examples

Models analogous to [A] that are clearly described are not common in the literature, but Hutchinson (2016) did find and discuss some (Rosén, 2013; Seiniger et al., 2013; Suzuki et al., 2014; Classen, 2015; Lemmen et al., 2013; Coelingh et al., 2010; Aoki et al., 2011).

Examples of models include the following.

- Those in Table 1 of Suzuki et al. (2014) have two braking strengths. Transition to braking is triggered by time to collision being sufficiently small. Cho et al. (2014) use a three-strength braking rule.
- In Lee et al. (2014), the rule for operation seems to be: braking with deceleration a is commanded when distance to an obstacle is less than the stopping distance, this being calculated from a, v, and rate of ramp-up of braking.
- Classen (2015) is concerned with modelling reaction to a pedestrian coming from the side. The model distinguishes between one to whom there is a clear line of sight, who can be tracked, and to whom reaction is quick, and one who emerges from behind an obstacle and to whom reaction is slower. Other features are that the pedestrian is presumed to be very close, and that there is a ramp-up of braking.
- Aoki et al. (2011) considered possible conditions for braking by drivers in a traffic stream. A simple idea is that braking is initiated if the ratio of relative distance to relative velocity is less than some constant. They then modified this with perceived distance and perceived relative velocity, and by including deceleration in the calculation.

See also sections 8.1.4, 9.1, and 9.2 of Hutchinson (2018a).

Examples of alternative or more complex features of AEB operation are as follows.

- Weak braking.
- "Priming" of the braking system. This refers to the possibility that the braking system might be put into a state such that it could operate after less delay than usual. That is, the vehicle might become primed at a time

t_2 after there is a challenge within a distance d_2, and that emergency braking is commanded at a time t_1 after the vehicle is both primed and within a distance d_1 of the challenge.

- Model [A] refers to an obstacle directly ahead. This means within an area whose width is approximately that of the vehicle projected forward. It would be possible to specify a lateral distance l as an additional characteristic of an AEB system, with the relevant area being the width of the vehicle plus a further distance l (which might be positive or negative) on each side, as in Rosén (2013).
- As well as braking, steering might be a possible response (e.g., Brännström et al., 2010; Hayashi et al., 2012, 2017; Seiniger et al., 2013). A simple idea that successful avoidance by steering might imply that time to collision needs to be sufficiently big was described in section 8.1.3 of Hutchinson (2018a).

7. Movement of a car in collision

7.1 Introduction

I hope this book will be of interest to vehicle designers and to accident investigators. But it is not primarily aimed at them. This chapter, on the collision of a vehicle with another vehicle, and the next chapter, on the movement of a car occupant and their collision with the car interior, can therefore be brief.

The present chapter is based on applied mathematics that you may have learnt at school. Other relevant literature includes Grime and Jones (1969), Grime (1987, chapter 6), and Mahmood and Fileta (2004, section 2.5.2.1).

An impact lasts about a tenth of a second. Looking ahead to chapter 8, injury to an occupant occurs when they strike some part of the car interior. That might be the steering wheel, windscreen, or instrument panel if they are unrestrained, or the seat belt and air bag. If they are unrestrained, this occurs approximately at the end of the vehicle impact. (See especially section 8.2 for the movement of a car's occupants in a crash.)

Tyre forces may be of great interest before the impact (e.g., in understanding loss of control) and after the impact (e.g., in reconstructing the impact from the vehicles' final positions and marks on the road). But during the impact itself, they can be neglected in comparison with the impact forces.

I have not discussed theory on loss of control of vehicles or overturning, i.e., such topics as failure to follow road curvature, spinning, overturning without "tripping", overturning because of tripping by a kerb or something else, and vehicle rotation when striking a barrier at an angle.

The three sections below are on head-on, rear, and side impacts.

7.2 Head-on impacts

The simplest geometry of collision is sufficient for this book. (Nevertheless, there will be some consideration of rear impacts and side impacts in sections 7.3 and 7.4.)

- Head-on.
- The vehicles approach along the line joining their centres of gravity.
- They are directly facing each other along that line.
- The collision is centre front to centre front.
- After collision there is no rebound (the coefficient of restitution is zero).

Concerning the occupants' injuries, what matters is the velocity change of their vehicle. In some crashes, intrusion into the occupant compartment is important in causing injury, and there are a few crashes in which significant injury occurs in some further impact after the first, but this book concentrates on the usual types of accident, as discussed in chapter 3.

The velocity change may be determined as below. It is necessary to keep a clear head about the signs of the various velocities: head-on impacts are being discussed, and the easiest thing is probably to say that v_1 is positive and v_2 is negative, as the movement is in the opposite direction.

- Let the masses of the vehicles be m_1 and m_2, and let the velocities be v_1 and v_2.
- After the collision, the two vehicles move as one body, mass $m_1 + m_2$ and velocity v.
- The law of conservation of momentum implies the following equation.

Momentum before = Momentum after

$$m_1.v_1 + m_2.v_2 = (m_1 + m_2).v$$

The change of velocity of vehicle 1 is

$$v - v_1 = ((m_1.v_1 + m_2.v_2) / (m_1 + m_2)) - v_1$$

$$= (v_2 - v_1).(m_2 / (m_1 + m_2))$$

$$= (v_2 - v_1).(1 / (r + 1)),$$

where r is the ratio of vehicle masses, m_1/m_2. (This definition is different from the definition of R. In section 2.4.2, R was defined as the ratio of the mass of the lighter vehicle to the mass of the heavier vehicle.)

The change of velocity of vehicle 2 is

$$v - v_2 = ((m_1.v_1 + m_2.v_2) / (m_1 + m_2)) - v_2$$

$$= (v_1 - v_2).(m_1 / (m_1 + m_2))$$

$$= (v_1 - v_2).(1 / (1 + (1/r)))$$

For example, suppose two vehicles, each of mass 1 tonne and each travelling at 50 km/h, collide head on.

- Common sense tells us, from the symmetry of the collision and our assumption that there is no rebound, that both vehicles must be stationary after the impact has finished, and both must have a velocity change of 50 km/h.
- The above equation does indeed give that result.

$$v - v_1 = (-50 - 50).1 / 2$$

$$= -50.$$

Remember that the movements are in opposite directions, so v_2 is -50 and v_1 is 50.

The features of the above equation may be described as follows.

- As regards the velocities, what matters is the relative velocity at impact.
- As regards the masses, what matters is the ratio of the mass of one's own vehicle to the mass of the other vehicle.
- As regards injury to a vehicle occupant, what matters is the velocity change of their own vehicle. The velocity change is a proportion of the relative velocity of the two vehicles. That proportion equals the mass of the other vehicle expressed as a proportion of the total mass of the two vehicles.

The ratio of the sizes of velocity change is the reciprocal of the ratio of masses: size of change of velocity of vehicle 1 divided by size of change of velocity of vehicle 2 is $1 / r = m_2/m_1$. (The reason for referring to "size" of velocity change is in order to be able to ignore the negative sign. The velocity changes are in opposite directions.)

Properties of the front of each vehicle, such as its stiffness, do not affect velocity change. They are of interest in some contexts, such as accident reconstruction. Neilson (1969, Appendix 5) considers the case of head-on impacts between vehicles that differ in frontal stiffness (as well as mass). The cases of (a) proportional increase of resistance with distance of crush, and (b) resistance constant whatever the distance of crush, are included. (For these cases, see also Neilson, 1973, Appendix 2.) There is some further comment in section 8.4.

7.3 Rear impacts

Analysis of rear impacts is very similar to that of head-on impacts. There are some obvious differences.

- The relative velocity at impact is usually much less than for head-on crashes. The proportion of casualties killed and the proportion seriously injured are correspondingly lower.
- There is a striking and a struck car. For the driver of the striking car, there is a frontal impact. Measures taken to protect occupants in other frontal impacts will be useful for this type of crash also. For the driver of the struck car, there is a rear impact. I am describing this as unusual (see section 3.2) and not of central interest for this book.
- Occupants of the struck car are protected by the seat backs.

7.3.1 Blame in rear impacts

When better information is not available, the driver of the striking vehicle is often thought to be blameworthy (for example, failure to pay attention, or failure to maintain sufficient distance from the vehicle ahead), and the driver of the struck vehicle is correspondingly thought to be innocent.

With large accident datasets that have only routinely-collected data, there may be no way of fully considering how much each driver and vehicle was to blame for a crash. The following rough method may therefore be adopted for estimating how blameworthy in crashes generally (not in some specific crash) is a particular combination of driver and vehicle such as a young driver in a specific model of car.

- Driver-vehicle combinations in single-vehicle crashes might be considered most to blame.
- Driver-vehicle combinations struck in rear-end crashes might be considered least to blame.
- The ratio of these numbers is then considered to reflect the risk associated with the particular combination of driver and vehicle.

That gives a rough idea of the approach. It might be considered an example of the induced exposure method of estimating risk, see Hutchinson (2018a, section 23.7 and Appendix 8).

7.3.2 Neck injury in rear impacts

In some datasets, there is information about nature of injury. And in some of these, there are very many minor neck injuries to occupants of the struck vehicle in rear-end crashes. (This is often referred to as whiplash.) Furthermore, in some datasets that do not have information about nature of injury, there appears to be a disproportionate number of injuries to occupants of the struck vehicle in rear-end crashes.

I am not a specialist on this topic, but nevertheless I feel I should comment, as rear-end crashes can appear to be numerically so important.

- After a road accident, money often becomes important, for medical treatment, vehicle repair, and other compensation. From time to time, newspapers report bad behaviour by insurance companies or by claimants. It is credible that bad behaviour sometimes occurs.
- I do not think it is proven that bad behaviour such as exaggeration of a minor injury is the main feature of the datasets concerned. It may be that a neck injury is often in the forefront of the mind of the sufferer: whichever way they look, they move their head, and feel pain.
- Such pain typically lasts only a small number of days.

It may be appropriate to describe some road crash datasets as being distorted by the reporting of this type of injury accident.

7.4 Side impacts

In this type of crash, one car hits the side of another. This often happens at intersections. There is a striking and a struck car. The striking car has an approximately frontal impact. Measures taken to protect occupants in other frontal impacts will be useful for this type of crash also. The struck car has a side impact, which I am describing as unusual (see section 3.2) and not of central interest for this book.

My impression is that not as much is known about intersection accidents and side impacts as might be expected. This may be because of the difficulty (in the case of accident data routinely collected by the police) of discovering what happened and recording it accurately. The recording of even a head-on crash can occasionally be utterly misleading in individual cases. With a more complicated category such as intersection crashes, it is unfortunately often impossible to know (in routine data) which direction each car was travelling, or which was the striking car and which was the struck car.

For the movements of vehicles in side impacts, see section 6.6 of Grime (1987). For equations, see Grime and Jones (1969, especially pp. 114-120, 112-113, 101-105). Because of the rotations of the vehicles, the equations are fairly complicated.

> Neilson (1973, section 7) gives an example of an angled impact in which the calculated post-impact movement of the cars is sensitive to the assumptions made.

I am unsure whether it is practicable to estimate post-impact velocities in any reasonably simple way.

The relative velocity of the two cars tends to be lower in side impacts than in head-on crashes, and the severity of injury from the usual mechanisms of injury tends to be lower. But in some side impacts, the striking car directly hits a part of the struck car that has someone sitting behind it (e.g., the driver's door). The emphasis of attempts to mitigate crashes is thus rather different from head-on crashes --- details of the design and strength of the side of the car become of great importance.

Much the same also applies to a car's side impact with a narrow object such as a tree or a post.

8. Movement of a car's occupants in a crash

8.1 Introduction

As mentioned at the beginning of chapter 7, injury to an occupant occurs when they strike some part of the car interior. That might be the steering wheel, windscreen, or instrument panel if they are unrestrained, or the seat belt and air bag. If they are unrestrained, occupant impact occurs approximately at the end of the vehicle impact.

Much of this chapter is based on Grime (1966). See also Grime (1987, chapter 7) and Chou (2004). I should note that in the 1960's in Britain (as in other countries), the great majority of car occupants did not wear seat belts, and airbags were not available.

8.2 Types of crash

Grime sets out the types of accident he is most concerned with.

- Frontal impacts, because these are the most frequent injury-producing types.
- Those involving fatal or serious injury.

Concerning the concentration on serious accidents, Grime is explicit (p. 4) that "As a result of making this choice, there may be a greater risk of slight injury in minor accidents than would be the case if the primary consideration were to prevent slight injuries". Because there is only a limited distance for a restraint to operate in, bottoming out (see section 1.6) is always a potential problem. Thus a stiff restraint will protect at higher speeds and from severe injury (because it does not bottom out), but it may itself cause minor injury at low speeds. This applies to seat belts just as it does to a car bonnet (see section 9.2.3). A seat belt should prevent an occupant from striking the car interior. A bonnet should prevent a pedestrian's head from (in effect) striking any very stiff structure of the engine compartment.

In agreement with this, the tone of the text at p. 1297 of Miller et al. (1996) is that it is important to avoid padding that is too soft.

8.3 Forward movement

Grime considers the movement of a front seat occupant when a car strikes a rigid barrier. Simplifying assumptions are: horizontal seat pan, zero friction between it and the occupant, legs can move forward.

After the first moment of impact, the vehicle occupants continue to move forward. That is, as slowing of the passenger compartment commences, the occupants start to move forward relative to it. An unrestrained front seat passenger strikes the windscreen or instrument panel with a relative speed almost equal to the initial speed of the car. A driver is closer to the steering wheel than the passenger is to the instrument panel, and strikes it with a slightly lower relative speed. The presence of the steering wheel is protective. (Intrusion by the steering column is dangerous, but is a different issue. It may have occurred not infrequently in crashes Grime was familiar with in the 1950's and 1960's.)

An occupant restrained by a seat belt, on the other hand, benefits from space in front, so that the belt can extend.

Because of the above, it is expected that an unrestrained driver will tend to be a little less seriously injured than an unrestrained front seat passenger. Cross-tabulated data summarised in section 15.3 of Hutchinson (2018a) shows that there is a difference in this direction in the case of nonoverturning accidents. The data is from Great Britain, 1969-1972. The great majority of car occupants did not wear seat belts at this time.

I might mention some papers pioneering the scientific study of injury to vehicle occupants.

De Haven (1942) describes a number of cases of falls from heights, in which injury was relatively minor because the distance of deceleration was some inches, and therefore acceleration was much less than if the impact surface had been rigid. De Haven appreciates the potentially life-saving strategy of a car occupant being in contact with the car at the moment of impact of the car. He comments that a 50 mile/h car crash usually involves a stopping distance greater than 60 cm, and thus the occupants could experience a relatively mild impact if they could take advantage of this distance through being in contact with the vehicle structure. (Of course, an example of "being in contact with" is to be strapped in with an inextensible seat belt.) DeHaven (1946) notes that an aircraft control wheel that becomes jammed in a rearward position is protective, like a shoulder harness.

Harper (1953) summarises the physics of injury as follows. A vehicle collides with a solid object at 13.4 m/sec, and the vehicle crushes 0.61 m. Deceleration is 15 g. "But how does the vehicle occupant behave in such a crash? At the moment of impact he has the same velocity as the vehicle. As the vehicle crashes to a full stop he continues forward at almost the same speed of 30 miles per hour [13.4 m/sec] and collides with the dash and windshield. By the time his body reaches these objects they are at rest, or very nearly so." Assuming stopping distance is 0.0508 m (crushing of the human and the vehicle interior, combined), deceleration is 180 g.

> Harper's statement is the earliest of its kind that I know of, but there may have been earlier similar statements elsewhere --- perhaps in the work of De Haven, of the (U.K.) Flying Personnel Research Committee, or in foreign-language sources.

Harper suggests the occupant should wear the car, as he or she might wear a suit of armour. "But for some unexplained reason the teachings of physics have never been understood or accepted by the motorist --- so, rather than 'strap on' the vehicle and take advantage of its protective armour in a crash, the motorist watches the vehicle crash relatively slowly to a stop and then dashes himself violently to pieces against its interior! This makes no sense at all, but it is still standard practice after 50 years of automotive accident history." (Of course, "relatively slowly" means that the vehicle crush has a duration of about 0.1 sec, and "dashes himself violently" means that the impact of the human has a duration of a tenth or a twentieth of that.) Furnas (1935, p. 3) also showed understanding. "Since the occupant .... continues in the old direction at the original speed, every surface and angle of the car's interior immediately becomes a battering, tearing projectile, aimed squarely at you --- inescapable."

8.4 Unrestrained and restrained car occupants

Grime (1966, pp. 8-9) considers the following example. Impact speed = 50 km/h, final deformation of front of car = 60 cm, distance from the occupant to the car interior = 41 cm (both head to windscreen and body to instrument panel), shape of the deceleration pulse is half a sine wave. Results were as follows.

- When an unrestrained occupant has moved forward 41 cm relative to the car, he or she strikes the car interior at a relative speed of 47 km/h, and the car itself has only 0.5 cm further to move. That is, there is very little extra distance available to help in reducing the force necessary to stop the occupant. Grime adds that "The padding and instrument panel, if very well-designed, may perhaps deform by up to 15 cm (5.9 in) giving a total stopping distance for the body of 15.5 cm (6.1 in); the average deceleration of the passenger's body must then be at least 64 g."
- Now consider a restrained occupant, with a seat belt slack of 2.5 cm. This occupant makes contact with the belt at a relative speed of 10 km/h, when 28 cm of the car's crushing distance remains. Furthermore, the seat belt can stretch. If it stretches 30 cm (i.e., most of the available distance), the total stopping distance is then 58 cm. The occupant's average deceleration is 17 g.
- The shape of the deceleration pulse makes some difference to the numbers, but not much. For the same example (50 km/h, 60 cm, 41 cm), the occupant's impact speed is 39 km/h in the case of the deceleration pulse being a front-loaded triangle. (That refers to acceleration being highest at the very beginning of the impact, and decreasing linearly to zero.) That might be considered a very worthwhile improvement on 47 km/h, but it is small compared with the improvement that results from wearing a seat belt.

If it is assumed that the deceleration pulse is of a specific shape (e.g., half a sine wave, square, triangular), various results may be obtained by straightforward (though sometimes complicated) algebra. This has been done both in the context of the pulse (of approximate duration 0.1 sec) experienced by a car in a frontal impact (e.g., Grime, 1966), and in the context of the pulse (of approximate duration 0.01 sec) experienced by a human when striking the interior or exterior of a car (e.g., Chou and Nyquist, 1974).

For an unrestrained occupant, the design of the front of the car has little effect on injury severity, as crushing of the front is complete before the occupant strikes the interior. If seat belts are worn, frontal design does matter to some extent. If the collision is offset (i.e., the overlap of the vehicles is small), deformation is larger, impact duration is longer, and thus the car interior may still be moving when the occupant strikes, leading to reduced injury; and the car's front design may matter in this case also. It should be added that prevention of intrusion is very worthwhile (e.g., by structures of high strength).

8.5 Sources of injury

From section 4 (p. 6) of Grime (1966):

> "The occupants of cars are injured by having large forces applied to their bodies, and the principle of all safety devices, such as padding, yielding steering wheels, and seat belts is that of reducing the force necessary to bring the body to rest by making it operate over the greatest possible distance. Force multiplied by distance equals energy, and the greater the distance the lower the force needed to dissipate a given amount of energy --- in this case the kinetic energy of the occupant's body. For a safety device, this distance may be obtained in two ways. (a) The occupant may be tied to or in contact with the car and may decelerate with it, i.e., use may be made of the car's own crushing distance. (b) The device itself may deform or stretch."
>
> (I should note that I have changed a few words here: I have referred to occupant rather than passenger, and to crushing distance rather than stopping distance.)

In Grime's account, the "safety device" may refer to the dashboard of the car, especially if padded. Two things are of particular interest, as they will correlate with severity of injury: the crushing distance remaining when the occupant touches the safety device, as this distance is in principle available for decelerating the occupant as gently as practicable; and the speed of striking the safety device, as this will itself cause injury if it is high enough and the safety device is stiff enough.

A crash helmet is an example of a safety device. Some people have wished that vehicle occupants would use a helmet, headband, or other head protection (McLean, 1979; McLean et al., 1997; Anderson et al., 2000; Ponte et al., 2002).

8.6 How to improve the secondary safety of cars

From section 5 (p. 10) of Grime (1966):

> "There are at least three ways in which it might be possible to make seat belts more efficient: (a) by improving their load/extension characteristics, (b) by increasing the restraining force applied to the occupant's body, and (c) by making alterations to cars to enable the belts to work more efficiently."
>
> (I again have referred to occupant rather than passenger.)

As to (a), this means making force less strongly dependent on extension. That is, increasing the force at small extensions and decreasing the force at high extensions.

As to (b), Grime makes a case that the maximum force could be increased (above 20 g) without unacceptable levels of injury being caused directly by the seat belt. Grime does not spell out the motivation for this, but it is evidently to increase the speed for which the available distance in front of the occupant is sufficient.

As to (c), four requirements are identified.

- The seat and the seat belt should be designed as a unit so that belt and seat work together to the best advantage. Assuming the belt to be very stiff, one of the options would then be for the belt to hold the occupant tightly to the seat, with the whole seat sliding forward.
- The space in front of the occupants should be of the right dimensions to allow the greatest possible extension of the belt.
- The passenger compartment should remain intact and retain its shape at speeds at least up to those at which fatal injury occurs despite a seat belt and interior padding.
- The crushable front of the car should be designed to produce the most favourable deceleration conditions for the operation of the seat belt. This means greater force very early in the impact, and Grime advocates greatly increasing the strength of the front bumper and its supports. However, he may not have given sufficient importance to pedestrians' legs: the bumper itself should probably be designed with a pedestrian's leg in mind.

Throughout this book, I am concentrating on ordinary or typical road accidents (see section 3.2). Part of my definition of an ordinary or typical road accident is that there is no significant intrusion into the passenger compartment. This is likely to be more difficult to achieve in the case of some types of vehicle --- I have in mind forward-control vans and very small cars.

8.7 Methods and equations used

The methods by which Grime obtained the above results may be summarised as follows.

Firstly, Grime's Figure 11 shows the amount of movement of the occupant relative to the car, over the course of the acceleration pulse, as a function of how much crushing of the front of the car has taken place. Both variables are in normalised form, in the sense that they have been divided by the final amount of crushing of the car. It might be convenient if the relationship did not depend on the shape of the acceleration pulse, but in fact it does depend on the shape to some extent.

Grime gives the following example. Suppose there is a safety device 20 cm from the occupant, and the crushing distance of the front of the car is 100 cm. In this case, the ratio is 0.2. Suppose acceleration is constant during the duration of the pulse (uniform acceleration). Then, from the curve plotted, 0.2 corresponds to crushing being 0.7 of the final crush. Thus 30 cm remains available. This is important, as it is potentially usable for deceleration of the occupant.

Secondly, Grime's Figure 12 shows the relative speed with which the occupant strikes the safety device as a function of the amount of movement. Again, both variables are normalised. That is, relative speed is expressed as a proportion of impact speed, and the occupant's forward movement is expressed as a proportion of final vehicle crush.

Continuing the example, if the normalised distance of the safety device is 0.2, then (in the case of uniform deceleration) the relative speed can be seen to be a fraction 0.44 of the original speed.

Thirdly, Grime's section 10 (Appendix) derives the equations from which his Figures 11 and 12 are plotted, for six different shapes of the acceleration pulse.

8.8 Vehicle mass and occupant injury: The contrast of two-vehicle and single-vehicle crashes

In two-vehicle crashes, velocity change depends on the mass ratio (section 7.2), and injury is usually worse in the smaller car.

In single-vehicle crashes (and in two-car crashes in which the cars are of approximately equal mass) at a given speed, injury ought to be similar whatever the mass of the car. As expected, British data shows no effect (Grime and Hutchinson, 1979), but surprisingly American data shows a strong effect (Evans, 1991, pp. 64-77; 2004, pp. 79-82).

My opinion is that there are a number of reasons why a small protective effect of greater mass is credible, but not a big effect. Appendix 6 discusses reasons why the American data may be misleading and is certainly not compelling.

9. Human impact

9.1 Introduction

Head injury is one of the most frequent reasons why people die in accidents. It has therefore received a lot of attention from researchers. The most common mechanism of injury is blunt impact, and much of this chapter is relevant to other types of blunt injury, also.

First, this chapter will describe tests using a pedestrian headform. Section 9.2 will discuss the principles for minimising the danger posed by a car's front (especially the bonnet) to pedestrians and other vulnerable road users. (Vulnerable road users is a phrase used to include pedestrians, cyclists, motorcyclists, and others outside a vehicle.) In the case of a pedestrian, there is a direct impact to the person. In the case of a vehicle occupant, the situation is more complicated, as there is an impact to the vehicle first, and subsequently there is an impact to the person (involving the restraint system, or occurring when the person contacts the vehicle interior).

Second, that type of test will be contrasted with others that are, or might be, carried out on some other manufactured object. The headform tests will be put into the context of four simple types of test (sections 9.3 - 9.5). The chapter concludes with a discussion section.

In designing a test, one would like to know what physical quantity is most closely responsible for injury. Possibilities include acceleration of the head (or other body part) as a whole, force, and deformation. Although this chapter will not answer this very difficult question, a number of important issues will be identified and clarified, even if a gap remains between physical variables and biological effects. Sections 9.3 - 9.5 do at least serve as a warning that results that might be obtained for the pedestrian headform tests will not necessarily be transferable to other types of impact test. Chapter 3 of Hutchinson (2018b) is a longer discussion of the matters in this chapter.

The conclusions are in a sense elementary, but are probably unfamiliar to many people. Even specialists in one field of application (e.g., pedestrian head injury) may not know much about another (e.g., chest injury from a punch by a robot).

- Only blunt injury is considered, not injury from penetration or from gross crushing.
- Only injury from translational (not rotational) movement is considered.
- The geometry of the impact is assumed to be the simplest, as when an object is dropped on to a flat surface.

Much of section 9.2 is based on part of Hutchinson et al. (2011). Chapter 17 of Hutchinson (2018a) and Chapter 3 of Hutchinson (2018b) are similar to parts of this chapter. A highly relevant book is that by Simms and Wood (2009).

9.2 Pedestrian impacts: Testing a car's front

9.2.1 Pedestrian injury

For pedestrians and other vulnerable road users, the exterior of the car can and should be designed to act as a cushion to protect them from stiffer structures underneath: the bonnet is softer than the engine and suspension components, for example.

Head injuries are a common cause of death in pedestrians. They are usually from vehicle contact rather than ground contact. The fronts of cars are low enough that, except in the case of very young children, the pedestrian’s head is not struck by the part of the vehicle that is near-vertical above the bumper, but the pedestrian's body rotates towards the bonnet. The head is then struck by either the bonnet or the windscreen of the vehicle. When the head is struck, it is accelerated by the impact. The mass being accelerated is approximately that of the head, but to some extent modified by the rest of the human body. This mass is referred to as the effective mass of the head.

9.2.2 Using a projected headform to test the exterior of cars

Part of the effort towards frontal design improvement involves projecting a free-flight instrumented headform against a number of locations on the exterior of the car and obtaining a record of its acceleration over the milliseconds of the impact. Such tests are conducted at a specified speed (11.1 m/sec, which is 40 km/h), and with headforms of specified mass (3.5 kg and 4.5 kg) and dimensions. The impact is usually angled, not perpendicular to the bonnet or other part of the car, and thus the perpendicular (or normal) component of velocity is less than 11.1 m/sec. Changes to specifications of the conduct of tests have occurred over the years, and are likely to continue. The acceleration trace is summarised by calculating the HIC (Head Injury Criterion). This is believed to reflect likely injury severity. (For how it is calculated, see section 10.2.) In other contexts, maximum (peak) acceleration is used for a similar purpose. HIC and maximum acceleration might be referred to as proxies for injury severity, or as injury response functions.

Before the head is struck, it is common for the lower leg and the upper leg to be struck. Correspondingly, there are tests of other locations on car exteriors using free-flight legforms. Head injury is more common as a cause of death, and so receives more attention.

The human head and the instrumented headform are (approximately) rigid in comparison with the car bonnet: they do not deform, the bonnet does. The human head and the instrumented headform are small in comparison with the car bonnet: they accelerate, the bonnet does not. Injury is regarded as a consequence of the acceleration. HIC is regarded as a reasonable method of summarising the acceleration trace for this purpose.

9.2.3 Bonnet stiffness

It might be thought that the less stiff, the better. But that is true only up to a point. The bonnet is protecting the pedestrian's head from contact with very stiff structures in the engine compartment of the car. It needs to be stiff enough to do that. Failure to do this is referred to as bottoming out. For a given speed, a good approximation to the optimal stiffness would be that for which the clearance distance (the space under the bonnet before stiff structures are reached) is exactly used up in stopping the headform. It might be better for stiffness to be slightly less than this, as even stiff structures are unlikely to be very injurious if the residual speed when they are reached is low.

That stiffness will not be optimal for lower and higher speeds. At lower speeds the stiffness will be too great, and at higher speeds the stiffness will be too low. Consequently, it would be desirable for results to be obtained for a range of realistic speeds. Testing is a potential means of obtaining those results, but sometimes a simple calculation may be sufficient. A similar conclusion applies to having a range of headform masses.

See also section 20.2.

9.2.4 Bonnet design

Partly as a result of impact testing, some general principles of bonnet design are now well understood.

- Projections and sharp corners and edges should be eliminated.
- There should be plenty of clearance distance between the underside of the bonnet and very stiff structures such as the engine and the suspension towers.
- One strategy for achieving clearance distance is to use a pop-up system, that quickly lifts the rear edge of the bonnet when activated.
- The bonnet should be yielding, but not so much so that it deforms too easily and fails to prevent the pedestrian’s head striking a very stiff structure (bottoming out). This dilemma requires some intermediate, optimal, degree of stiffness to be found.
- The very stiff structures underneath the bonnet should be made less stiff, or frangible.
- The coefficient of restitution (see section 1.6) for the pedestrian-vehicle contact should be low. The pedestrian should tend to stick to the bonnet; bouncing is more dangerous.
- If it is practicable to exercise some control over the shape of the acceleration pulse, the peak of this should be early rather than late in the impact. That is, the bonnet should be damped, i.e., be stiffer early in the impact (when speed is high and bonnet deflection is low) than later. The importance of high accelerations rather than low in causing injury might be thought to imply that for a given velocity change, the acceleration should be constant over the time the pulse lasts. However, high acceleration occurring early also disproportionately reduces the distance

travelled. Thus to minimise HIC under the constraint of a given available clearance distance, acceleration should be higher early in the impact (Okamoto et al., 1994). In the context of helmet linings, Cheng et al. (1999, p. 306) mention breakaway materials as a possible method of achieving a high force early.

See also Appendix 7.

The desirability of eliminating anything sharp or projecting, and of having a low coefficient of restitution, were appreciated by Wakeland (1962). Some years later, the account in Harris (1976) is considerably more useful, with a recommendation that "Hidden components should be terminated well below bonnet level to allow depth for deformation. Examples are the engine and fittings, front suspension and the side walls of the engine compartment." At about the same period, McLean et al. (1979, pp. 39, 42) drew attention to this issue from the perspective of pedestrian injury cases that had been investigated in Adelaide in 1976 - 1977.

The principles given here and in Appendix 7 apply to other large structures that the head may impact --- both in road safety contexts (e.g., the car interior), and in quite different contexts (e.g., sport, playgrounds, military).

In particular, there will always be a degree of concern that the choice of particular conditions (e.g., impact speed) in which to test will lead to a particular choice of stiffness, which will be too low to prevent bottoming out in more severe impact conditions (higher speed, greater effective mass).

9.3 Four types of impact

Other types of impact will now be considered. Concerning two objects that collide, there are four binary contrasts between them.

1. One is human, the other is inanimate.
2. One is moving, the other is stationary. (Although one is stationary, it is free to move, not clamped in position.)
3. One is large, the other is small. I am using these terms to mean that acceleration of the large or massive object is negligible, and thus all the acceleration is of the small object. If a small object is clamped in position, rather than being free to move, it must be considered to be the large object.
4. One is rigid, the other is deformable. I am using these terms to mean that deformation of the rigid or stiff object is negligible, and all the deformation is of the deformable or yielding object.

As to the first of these contrasts, attention is concentrated on what happens to the human. Or, more generally, attention is concentrated on the object that might be damaged. (This is usually a human, but the packaging of manufactured goods and the handling of fruits and vegetables are also important areas of application.)

As to the second of these contrasts, what matters is the relative velocity of the impacting objects, not the identification of which is moving and which is stationary.

The other two contrasts --- in respect of mass, and in respect of deformability --- will now be considered further. They imply four types of impact that need to be distinguished.

- Small rigid human, impact with large deformable object. Pedestrian headform tests are examples of this type. Other examples: tests of the car interior, and of various types of helmet.
- Large deformable human, impact with small rigid object. Example: human chest is struck by a hard ball.
- Small deformable human, impact with large rigid object. Examples: human chest is punched by a large robot, human head strikes concrete floor.
- Large rigid human, impact with small deformable object. Example: human head is struck by a plastic bullet.

This list is given largely in order to discuss injury from acceleration as contrasted with injury from deformation, and implications concerning proxies for injury.

Only one thing deforms, and only one accelerates. The softer thing (e.g., the bonnet, not the headform) deforms, and the smaller thing (e.g., the headform, not the bonnet) accelerates. Intermediate cases, in which the two objects are of comparable mass or comparable stiffness, are more complicated and are mostly outside the scope of the present discussion.

- When both masses need to be taken into account, the law of conservation of momentum can be used to work out their respective changes of velocity.
- When both stiffnesses need to be taken into account, it may be possible to work out a single stiffness that is equivalent.

See Hutchinson (2018b, section 3.7).

9.4 Proxies for injury: Contrast between acceleration and deformation

A test relevant to injury needs to measure something that reflects injury. I have referred to such a measurement as a proxy for injury, or an injury response function. HIC and maximum acceleration are examples, and were mentioned in section 9.2.2. Both these are based on acceleration. Such measures are only relevant when the human accelerates, that is, when the human is the small object in collision with a large object.

Other proxies for injury are based on deformation of a human (e.g., maximum deformation, and maximum Viscous Criterion VC_{max}). These are only relevant when the human deforms, that is, when the human is the deformable object in collision with a rigid object.

It appears that if the human is large and rigid, most of the common proxies for injury are unsuitable. Maximum force may be suitable. However, acceleration-based proxies may be relevant to the important problems of hard sports balls or less-lethal munitions striking the head: even though the velocity change of the human is small, acceleration of the head may be sufficient to be injurious.

9.5 Comments on proxies for injury severity

Cushions protecting against impact should be tested, and testing must use some measurement in place of injury. It is important to choose a measurement that is as appropriate as possible for the type of injury envisaged. The importance of biofidelity is widely appreciated, but the work of many researchers is largely restricted to one discipline or one source of injury or one part of the body. Biofidelity is a factor limiting generalisation beyond a specific setting. If a dependent variable based on deformation (such as maximum deformation of the human or the Viscous Criterion) is in use, the method for measuring deformation (e.g., a physical dummy, or a mathematical model) needs to be biofidelic in regard to deformation. If a dependent variable based on acceleration (such as maximum acceleration or HIC) is in use, the method for measuring acceleration needs to be biofidelic in regard to acceleration.

The various proxies for injury are affected by the conditions of the impact, such as its speed, the mass of the object that accelerates (e.g., a pedestrian's head), and the stiffness of the deforming surface (e.g., a car's bonnet). This will be shown in chapter 10.

The effects of the conditions of impact are different for the different proxies for injury. The effects may even be in opposite directions.

- HIC and maximum acceleration are quite similar concepts. Both are based on translational movement, not rotational; both are based on acceleration, not force or deformation or something else. Even so, an example is given in section 18.8.4 of Hutchinson (2018a) of a change in conditions giving a reduction in maximum acceleration and an increase in HIC. (The change of conditions involved changes of both mass and speed.)
- Despite that example, a change in conditions will usually change maximum acceleration and HIC in the same direction. It is more likely that a concept based on force or on deformation will behave differently.

Consequently, it is highly desirable to know which proxy for injury is most suitable. See, for example, King (2004). My impression is that there is considerable uncertainty among experts as to what concept comes closest to representing what causes injury.

- Martin et al. (1994) prefer acceleration, and I think that preference has been common for some decades. However, part of the reason may be the practicability of measuring acceleration with instrumented headforms and similar devices.
- For injury to soft tissues, including the brain, many people think that deformation, and perhaps rate of deformation, are important. According to Rowbotham (1949, p. 310), "Practically all the physics of closed cerebral injury resolves itself into distortion".
- For fracture of bone, including the skull, many people think that maximum force is important.

I am to some extent guessing about what "many people think" --- the experts are often very cautious in what they say.

I fear that for many years to come, progress may be very slow on two important questions. What physical quantity most closely reflects severity of injury? What is the probability of death at various values of that physical quantity? In addition, the issue of choice of proxy for injury is only one question among several. Other examples include the probable clinical implications of a specified value of HIC or maximum acceleration, whether the clinical meaning is the same for people of different head mass, whether extrapolation to different conditions of impact is valid, the accuracy or inaccuracy in experimental results, and so on. In view of all the other uncertainties, perhaps the issue of the proxy for injury should not be allowed to hold us back. Even if we knew what really mattered as regards brain injury, it would probably not be the same for skull injury. Perhaps it is necessary to treat predictions of the effect of change in conditions of impact as quite rough approximations.

9.6 Discussion

Injury severity is likely to depend largely on three things: (1) impact speed (the component perpendicular to the surface), (2) stiffness of the surface, (3) whether the surface bottoms out. (Angle of impact is used in calculating normal impact speed from impact speed.)

Several caveats need to be added to the previous paragraph.

- Effective mass is important in determining acceleration. I have omitted it from the foregoing list because it seems unlikely that we can control it.
- What happens to the human, including the injury and the injury severity, is affected also by the frailty of the human.
- Angle of impact may affect the mechanism of injury (e.g., translational or rotational acceleration).
- The part of body struck is likely to be important.
- I am thinking of injury from blunt trauma, not from impact with sharp objects, nor from being crushed.
- I have in mind head injury.
- If the human is wearing a helmet, then the surface is actually the combination of the foam of the helmet and the external object.
- There are a number of well-known difficulties with the concept and measurement of injury severity: we do not have a good measure of severity, we do not really know what physical quantity causes injury, fatal cases are rare, and so on.

Even with only three variables affecting injury severity, that means things are close to hopelessly complicated --- that is, if one had lots of data and attempted some sort of statistical analysis with an open mind and no guidance from theory.

10. Effects of speed (and other variables) on HIC (and other variables)

10.1 Introduction

It is sometimes foreseen that a particular manufactured object may strike or be struck by a human. In this case, a system of impact testing is often set up, including testing of any padding or cushioning that the object has. The example in section 9.2 was of the bonnet and other parts of a vehicle exterior. Other examples include the interior of a vehicle, a helmet lining, and the ground. The properties of these objects, such as stiffness, are important to injury and protection of the human.

Measurements are made during the test. In the case of head injury, the most frequently-used measurements are of the Head Injury Criterion (HIC) and maximum acceleration. These are believed to reflect likely injury severity and risk of death. They are dynamic measurements, reflecting movement and a realistic impact. They are not static measurements simply of stiffness.

> Some experts may think that high linear acceleration is the real cause of death and serious injury. Other experts may think that is not the case, but that HIC and maximum acceleration are nevertheless sufficiently correlated with the real cause to be useful (that is, to be useful in many, or perhaps only a few, circumstances). The real cause may be thought to be rotational acceleration, or the deformation of the skull and brain.

HIC and maximum acceleration are summaries of the acceleration pulse over the milliseconds of impact. They are calculated from the acceleration pulse recorded by an instrumented headform. Surprisingly little seems to be known about how they depend on conditions of the impact such as speed, mass (of the headform), and stiffness (of the deforming surface). There are at least two contexts where knowledge of these relationships would be very valuable: the real-world consequences of impacts in different conditions; and more narrowly, in impact testing, there may be a desire to calculate equivalences between tests conducted with different choices of conditions. That is, measuring HIC in one known set of conditions is likely to imply something about what HIC would be in another known set of conditions.

The starting point in this chapter is to assume that a specific differential equation relates the force at any instant during the impact to instantaneous displacement (deformation) and instantaneous velocity. Consequences are then derived mathematically. The simplest assumption is that of a linear spring; more complex and realistic assumptions, including nonlinearity of the spring and damping being present, are also considered. For the differential equation considered, it will be shown that maximum acceleration and HIC are proportional to power functions of initial velocity and mass of headform; expressions are obtained for the exponents in terms of the exponent applying to the nonlinear spring. There is more on the topic of this chapter in chapters 4 - 6 of Hutchinson (2018b); see chapter 18 of Hutchinson (2018a) also.

10.2 Force, represented in a differential equation

Notation will be that x is distance, its first differential velocity is x', and its second differential acceleration is x''. The symbol $\propto$ means "is proportional to".

Consider a normal (perpendicular) impact of a headform of mass m with a car exterior. (An angled impact is assumed to be represented by the normal component of the velocity.) The force on the headform at any moment is assumed to depend on the instantaneous distance travelled after first contact (i.e., the deformation of the exterior) and on instantaneous velocity. The acceleration of the headform is the ratio of force to mass. Hence the differential equation will take the following form:

m.x'' = some function of x and x'

The initial conditions at time = 0 are x(0) = 0 and x'(0) = v. It is also understood that force becomes zero after the headform and vehicle part contact. This equation (if it is sufficiently near correct) represents causation, and so will permit inputs such as speed and mass to be connected to outputs such as maximum acceleration and HIC.

Another output is maximum displacement of the bonnet (the symbol S will be used for this). If this were to exceed the distance between the bonnet and a harder structure beneath the bonnet, bottoming out would occur and HIC would increase dramatically. The equations for force to be used below are assumed valid before bottoming out occurs. Calculation and prediction of maximum displacement are useful in warning when validity might end.

The Head Injury Criterion HIC is $[av(a)]^{2.5}.(t_2 - t_1)$, where av(a) is average acceleration over a time period from t_1 to t_2, with t_1 and t_2 chosen so that the resulting HIC is maximised, and average acceleration is velocity change in the relevant period divided by $(t_2 - t_1)$. It is sometimes required that $(t_2 - t_1)$ does not exceed a prespecified length of time, e.g., 15 msec. This detail will be ignored.

Differential equations are often solved, in the sense that displacement x is obtained as a function of time, and similarly velocity x' and the acceleration pulse x'' are obtained as functions of time. There is no immediate need for this in the present context; instead useful results are obtained without an explicit expression for x(t), x'(t), or x''(t).

10.3 Linear and nonlinear springs

10.3.1 Undamped linear spring

For the undamped linear spring, the term in velocity x' is absent, and the differential equation is

$$x'' + (k/m).x = 0$$

The constant k is the coefficient of stiffness. This equation, it so happens, can be solved by elementary means: the acceleration pulse is half a cycle of a sine wave.

If there are two or more linear springs in series, there is a single linear spring that is equivalent. Miller et al. (1996) modelled the upper interior of cars being subject to impact with a headform as four springs in series: the polymer skin of the headform, the interior trim, padding, and the vehicle structure (e.g., A pillar).

The linear spring implies the coefficient of restitution (the ratio of final speed to initial speed) is 1. This is highly unrealistic for pedestrian (and many other) impacts. For these, the coefficient of restitution is close to 0. That is, the pedestrian's head (or the headform in a test) bounces back with a speed that is fairly negligible. In practice, therefore, the above differential equation would be modified by assuming it applies only until the moment of maximum deformation (and force is zero after that). The acceleration pulse would be a quarter of a cycle of a sine wave.

10.3.2 Undamped nonlinear spring

A simple way of generalising the undamped linear spring by making the spring nonlinear is:

$x'' + (k/m).x^n = 0$

This permits the spring to become either more or less stiff as displacement increases. Increasing stiffness is implied by $n > 1$, and decreasing stiffness by $n < 1$. Some results for this case were given by Martin (1990), who was chiefly concerned with athletes' impacts with playing surfaces. His opinion (p. 80) was that for playing surfaces impacted by an adult, a value of exponent n of about 3 was typical. (See also Martin et al., 1994.)

10.3.3 Special cases

In some circumstances, the case $n = 1.5$ is important, arising from linearity between stress and strain together with the geometry of a sphere. This is termed Hertzian impact (see article 142 of Timoshenko and Goodier, 1970).

The case $n = 0$ was considered by Neilson (1969), in the contexts of padding that might be struck by a car occupant and of crush of a car's front. This may have been partly for the tractability of the algebra. But Neilson (1969) gives some attention to resistance that decreases with crush, so I think it more likely that Neilson considered $n = 0$ of genuine interest. For $n = 0$, maximum force and maximum acceleration are minimised, for a given amount of energy absorption. For crush of a car's front, see also Neilson (1973), Moore (1970) (who regards approximately constant deceleration as typical), and section 17.9 of Hutchinson (2018b).

For padding that might be struck by a human, there is at pp. 446-448 of *Research on Road Safety* (Road Research Laboratory, 1963) a comparison of springs that are linear, that become increasingly stiff, or that become decreasingly stiff.

- The chief constraint is the thickness of the padding. In effect, that is, there is only space for a particular distance of crush.
- As regards causation of injury, we might consider only the maximum acceleration or force. (This is an approximation, but there is reasonable confidence that maximum acceleration or force is more important than the time for which it lasts.)
- The priority is to prevent death and mitigate severe injury.
- This suggests use of a spring of decreasing stiffness (as occurs when n is less than 1).
- It is admitted that the disadvantage is unnecessarily severe impact at low speeds.

Regarding the spring being of decreasing stiffness (n being less than 1, and perhaps being close to 0), DeHaven (1946, p. 16) had noted the advantage of this: light sheet metal "appears to be more satisfactory than deep sponge rubber or any other known padding, because full energy absorption begins with the first denting of the surface and continues without seriously increasing peak force or danger".

10.3.4 Proportionality results

For the above equation, some of the desired results may be obtained by the elementary method of equating the kinetic energy of impact to the energy absorbed. Let S be maximum displacement (maximum deformation).

- Energy is force integrated over distance, that is, $k.x^n$ integrated from 0 to S, which equals $k.S^{n+1}.(1/(n+1))$.
- This must equal kinetic energy of impact, $½.m.v^2$.
- Therefore S is proportional to $(m/k)^{1/(n+1)}.v^{2/(n+1)}$.

Further results are as follows.

- Force increases with displacement, and maximum force occurs when displacement is at its maximum. Thus maximum force is $k.S^n$, and is proportional to $k.(m/k)^{n/(n+1)}.v^{2n/(n+1)}$.
- Maximum acceleration is maximum force divided by mass, and is proportional to $(m/k)^{-1/(n+1)}.v^{2n/(n+1)}$.

A result for HIC cannot be obtained so easily (as far as I know).

10.4 A multiplicative damping term (Hunt and Crossley)

A simple way of generalising the linear spring to include a velocity-sensitive term (damping) is:

$$x'' + (k_2/m).x' + (k/m).x = 0$$

However, it is sometimes argued that this is unrealistic, and that the damping term should be 0 for both x = 0 and x' = 0 (Hunt and Crossley, 1975). That suggests a product term in powers of x and x'. A simple example incorporating a nonlinear spring ($n \geq 0$) is:

$$x'' + (k/m).x^n.(1 + (b/v).x') = 0$$

It is understood that b, k, and n remain constant, not only as time t elapses over the course of the acceleration pulse, but also if v and m change.

A divisor v is included in the damping term in the equation because then constancy of b in the equation implies constancy of coefficient of restitution when v changes, and that is thought to be approximately true empirically: see pp. 212-213 of Gonthier et al. (2004). A damping term proportional to $x^p.(x')^q$ was proposed by Hunt and Crossley (1975), and they gave particular attention to the case p = n, q = 1, as in the equation above. Anderson et al. (2009) suggested the equation be used to model pedestrian-vehicle contact. The divisor v may date from Herbert and McWhannell (1977). Models of this type are reviewed by Flores and Lankarani (2016) and Banerjee et al. (2017). In many of the models, x' appears in the form of the ratio x'/v.

It will be convenient to refer to this as the Hunt and Crossley model or equation. I am not sure, however, whether that is quite appropriate: Hunt and Crossley had in mind impacts such as solid steel with solid steel, and coefficients of restitution above 0.84 and perhaps much closer to 1 than that. In contrast, the coefficient of restitution is approximately 0.25 when a headform hits a car bonnet (Dutschke, 2013, section 3.5.2).

10.5 Proportionality results

It turns out that, for the above differential equation based on Hunt and Crossley, changes of m (and k) and v result in changes of the height and length of the acceleration pulse but do not otherwise change its shape (Hutchinson, 2013).

- Maximum acceleration A_{max} is proportional to $(m/k)^{-1/(n+1)}.v^{2n/(n+1)}$.
- Duration T is proportional to $(m/k)^{1/(n+1)}.v^{-(n-1)/(n+1)}$.

Consequently, proportionality results concerning HIC and maximum displacement can also be obtained (Hutchinson, 2013).

- HIC is proportional to $(m/k)^{-1.5/(n+1)}.v^{(4n+1)/(n+1)}$
- Maximum displacement S is proportional to $(m/k)^{1/(n+1)}.v^{2/(n+1)}$.

Headform mass m has a negative effect on maximum acceleration and HIC. This is a consequence of these injury response functions being based on acceleration rather than force. Maximum displacement of the car bonnet is positively related to m, as would be expected as increased m means more kinetic energy. As deceleration takes place over a longer distance, accelerations are smaller. In contrast, headform mass has a positive effect on maximum force.

For convenience, the exponents are listed in Table 10.1.

Table 10.1. Exponents of (m/k) and v, for maximum acceleration, pulse duration, HIC, and maximum displacement.

	Exponent of (m/k)	Exponent of v
Maximum acceleration A_{max}	-1/(n+1)	2n/(n+1)
Duration T	1/(n+1)	-(n-1)/(n+1)
HIC	-1.5/(n+1)	(4n+1)/(n+1)
Maximum displacement S	1/(n+1)	2/(n+1)

Maximum displacement S may be considered simpler than maximum acceleration and HIC, and it may be desired to have results for maximum acceleration and HIC in terms of maximum displacement.

- On the assumption that the shape of the acceleration pulse is quadratic, Mizuno and Kajzer (2000) algebraically demonstrated that HIC $\propto S^{-1.5}.v^4$.
- On the assumption of an asymmetric haversine pulse (as they call it), Zhou et al. (1998) algebraically demonstrated that HIC $\propto S^{-1.5}.v^4$.
- Figure 9 of NHTSA (1993), said to be the result of theoretical analysis, shows HIC versus S for three speeds. I have attempted to calculate what relationship underlies that Figure, and it is fairly clear that it is HIC $\propto S^{-1.5}.v^4$.
- For various shapes of pulse, dependence of HIC on S and v is given in equation (3) and Table 1 of Yang and Li (2019). Equation (4) and Table 1 of that paper also relate HIC to a measure of acceleration and v (and this is also a dependence of HIC on T and v).

The relationships given in Table 10.1 show that the proportionality relationship connecting HIC and S holds in more general conditions.

- Maximum acceleration is proportional to $S^{-1}.v^2$.
- HIC is proportional to $S^{-1.5}.v^4$.

These relationships will hold if m or k change. They will not apply if b or n change. Referring to different impact surfaces, it might be adequate to characterise many impact surfaces (or at least those of a particular type) by k alone, with b and n being constant.

10.6 An alternative theory

An alternative theory can be constructed by assuming that n = 1, but with something special occurring at initial contact. A suggestion for a simple special phenomenon at initial contact is as follows.

> Suppose that energy E is absorbed over a distance D; and after that, the Hunt and Crossley (1975) equation is followed, with n = 1. Energy E and distance D are regarded as properties of the surface, and are not affected by v, m, or k.

As n is taken to be 1, fitting of n to the data is no longer available as a way of describing or explaining the data. Instead, the size and nature of what happens at initial contact will have to do this.

The proportionality relationships already obtained (A_{max}, HIC, and S proportional to power functions of v and m/k) will apply, with the following modifications.

- Firstly, S - D replaces S.
- Secondly, an effective impact speed v_e replaces v. The equation connecting v_e to v is $½.m.v^2 = ½.m.v_e^2 + E$. (Initial kinetic energy equals final kinetic energy plus energy absorbed.)

In this form, there are two extra unknowns to be fitted to the data. The special cases D = 0 (with E to be fitted to the data) and E = 0 (with D to be fitted to the data) might be considered of interest if only one extra unknown were permitted.

Even if this theory is not adopted, the idea that impact speed as measured (or reported) is not valid might be plausible. This would suggest exploration of relationships that hold between dependent variables as v varies, without v itself being used. An example is the relationship between HIC and A_{max}. This will be considered in section 10.7.

As far as I know, the empirical evidence supporting the model considered in section 10.4 is not very strong. However, many people will consider the linear spring to be the natural starting point for a model, and that in section 10.4 does include this as a special case and does generalise it in two ways (nonlinearity in x, and a term in x'). And Hunt and Crossley and later researchers did have reasons for the form of equation used. In the application to a bonnet struck by a pedestrian, it might perhaps be generalised by supposing that the bonnet has some mass that is put into motion at the moment of contact. (For putting a mass into motion, see Hutchinson, 2018b, especially sections 5.4.3, 6.7.4, and 12.4.)

10.7 Relationships between outputs

In section 10.5 and Table 10.1, proportionality relationships between several inputs (m, k, v) and several outputs (T, S, A_{max}, HIC) were obtained. The final two paragraphs of section 10.5 considered some of the interrelationships between S, A_{max}, and HIC. Two further questions are now discussed.

The first question is whether high maximum deformation suggests high severity of injury, or whether it suggests low severity. Elucidating this helps us understand the nature of correlation. The following points are worth making.

- We are not referring to a situation where maximum deformation and severity are linked by cause and effect. Instead, the situation is that both are caused by something else, that is, by the impact.
- Speed of impact affects both maximum deformation and severity. High speed leads to high deformation and high severity. If we are considering a set of impacts that differ in respect of speed but in other respects are the same, there will be a positive correlation between maximum deformation and severity. High deformation will be an indicator of high severity.
- Stiffness affects both maximum deformation and severity. High stiffness leads to low maximum deformation and high severity. If we are considering a set of impacts that differ in respect of stiffness but in other respects are the same, there will be a negative correlation between maximum deformation and severity. High deformation will be an indicator of low severity.

Referring back to the first point, if association between two variables is due to their both being affected by a third variable, the association may be positive or may be negative, depending on what the third variable is.

The second question is whether HIC and maximum acceleration are equivalent concepts. In a sense, of course, it is obvious that they are not, as it is not possible to calculate one from the other. Nevertheless, they are to some extent similar. The following will clarify the relationships between them.

Suppose we measure both HIC and A_{max} in a number of experiments. We might find that HIC and A_{max} are highly correlated, and we might be able to obtain an empirical formula for calculating one from the other. However, this relationship will differ according to what the source of the correlation is. Is it, for example, due to variation in v, or m, or k?

From section 10.5, it is reasonable to suppose that A_{max} may be proportional to $(m/k)^{-1/(n+1)}.v^{2n/(n+1)}$ and HIC may be proportional to $(m/k)^{-1.5/(n+1)}.v^{(4n+1)/(n+1)}$. This will imply the following.

- If m and k remain constant and v changes, HIC is proportional to $A_{max}{}^{(4n+1)/(2n)}$.
- If k and v are constant and m changes, HIC is proportional to $A_{max}{}^{1.5}$.
- If m and v are constant and k changes, HIC is again proportional to $A_{max}{}^{1.5}$.

See also section 18.8 of Hutchinson (2018a) and section 6.5 of Hutchinson (2018b).

11. Testing contrasted with real-world variability: Measure-generalise-cost-average

11.1 Introduction

At present, it is common to presume that a test result at a specified choice of speed and other conditions is sufficient. This appears simple, but that appearance may be illusory. There are some difficulties that are hidden rather than non-existent, in particular concerning the choice of the single set of conditions for testing. Some people may say that a low test speed should be chosen because low speed impacts are far more common than high speed impacts, others may say that a high test speed should be chosen because it is the fatal and near-fatal impacts that are of most concern, and still others may argue for a typical impact speed in the middle of the distribution of real accident speeds. (Of course, the committees that decide these things take into account many other factors, notably ones of practicability.)

Alternatively, we might wish to know the level of safety in a wide range of real-world impact scenarios, and to have some sort of average available. The aim in this chapter is to propose a method of doing this. There has been some dissatisfaction for many years with having only a single set of test conditions (e.g., Horsch, 1987; Kanianthra et al., 1993; Korner, 1989; Searle et al., 1978; Viano, 1988).

The idea in this chapter was largely my colleague Robert Anderson's, and it occurred in the context of impact testing using a headform representing a pedestrian (see section 9.2). I put it into the form used in section 11.4.2. Our first account of the method was as Hutchinson et al. (2012), and this chapter is based on a later conference paper (Hutchinson et al., 2016). Chapter 20 of Hutchinson (2018a) and chapter 19 of Hutchinson (2018b) are similar to this chapter.

11.2 Outline of method

Some questions and answers might be helpful at this point.

- What is the starting point? A result obtained in closely-specified test conditions.
- What is the aim? To calculate the likely performance in the real world. There are two aspects to this: performance in conditions other than those in the test, and the averaging of performance over all conditions that occur.
- Does the concept of an average have any particular implications? Yes, it means that there must be a numerical quantity that can be averaged. In addition, there is an implication that it is appropriate to base decisions on the result. Such a quantity is often referred to as a utility (or a cost, or a value).
- How will the average utility be calculated? It will be based on the utility in a given set of conditions together with the probability of that set of

conditions occurring in the real world, and consideration of all sets of conditions.

- Are the relative frequencies of different sets of conditions known? To some degree, yes, there is information available about real-world accidents and their frequencies. The information is not usually very accurate, however.
- Is it likely that a utility will be recorded in the test? No, it is much more likely that something that is convenient for the physical process of measurement will be chosen. The measurement will need to be converted to the corresponding utility.
- Is the physical measurement known for every set of conditions? No, it is known only for the set of conditions used in the test. Many tests might be performed in order to cover the range of conditions that occur, or some theory might be available to generalise from one set of conditions to others.

This chapter will sometimes be written in terms of impact testing specifically, and sometimes in more general terms. For example, HIC and speed are specifically referred to. More generally, they would be the output obtained in the test, and the input that is specified for the test but varies in the real world.

The method is reasonably straightforward in principle. The following issues will be important.

- The need to do lots more tests in order to obtain the basic data on how HIC varies with speed --- or, alternatively, a theory about this is required.
- While it is hoped that HIC reflects or indicates likely injury, it is not itself a measure of injury.
- It is unlikely that it is sensible to average HIC. One person with HIC = 900 and one with HIC = 1100 is about as bad an outcome as two people with HIC = 1000, but this simple averaging is likely to be inappropriate for one person with HIC = 200 and one person with HIC = 1800.
- Despite the previous point, some sort of average or summary measure will be needed. That means that information about frequencies of impacts at different speeds will be required as input to the calculation.

One possible method (and perhaps it is the best method) of determining the level of safety in a range of scenarios is to test across the range of scenarios and combinations of scenarios. Something like this is indeed done, in that many different locations on a car exterior are tested or assessed in producing a summary rating for the car. Nothing said below should be taken as critical of that straightforward approach. But it may be possible to use theory to economise on the number of tests.

The following sentences refer to motorcycle helmet design, and appear in Gilchrist and Mills (1994, p. 217). "The compromise design should attempt to minimise the total harm to helmet wearers. The injuries predicted for a specific impact velocity and impact object should be weighted according to the frequency distribution found in accident surveys." That seems very similar to the aim expressed above. What will be proposed below is not very different from existing procedures in which two or more tests are conducted and the results weighted according to their importance, in order to give an overall summary of level of performance (Kanianthra et al., 1993, pp. 9-10).

- There is more emphasis on speed being a very important condition that varies from one accident to another.
- There is more emphasis on the possibility of using theory to estimate what test results would be if test conditions (in particular, speed) changed.
- Two components to importance are represented separately. One is the relative frequency of the condition (or combination of conditions) among accidents. The second is the cost (in particular, the likely severity) of accidents in that condition.

11.3 Proposed method: Measure-generalise-cost-average

The average is typically the appropriate number on which to base a decision. This is the end point of a calculation as described below.

What is of chief interest is injury. What is measured in an impact test is an acceleration pulse. This serves as a proxy for the injury. A contrast like this between what is of central interest and some measurable physical quantity is a feature of many other types of test. An acceleration pulse in an impact test is usually summarised by a single number: a calculation is carried out that results in the HIC.

Tests could be conducted at a number of different speeds. Alternatively, there may be some theory available concerning the dependence of HIC on speed (see chapter 10). Suppose that results are obtained, whether directly by testing or by some other method, at lots of different speeds. It is often impossible to understand so many results, and they need to be summarised. That is, an average needs to be calculated. Thus the results need to be numbers (and not words such as Good or Unsatisfactory). The number associated with a single test needs to be such that when several of these numbers are obtained, a decision can be made on the basis of the average. That is, they need to be "utilities" or "values" or "costs".

The proposed calculations are as follows.

- *Measure*. From the acceleration pulse obtained at one speed (or under one set of conditions), the HIC is calculated.
- *Generalise*. Either the test and HIC measurement are repeated for several speeds, or the results for various speeds are found using theory.
- *Cost*. Each HIC is converted to the corresponding cost.
- *Average*. From the costs at several speeds (or in several sets of conditions) together with the probabilities of these speeds occurring in the real world, the average cost is calculated.

11.4 Equation for average cost

11.4.1 Notation

Mathematics is used (section 11.4.2), but the meaning is spelt out in words. Notation is given below.

- x is the speed of impact of the car with the pedestrian (assumed to be the same as that with which the head hits the car); more generally, this is any quantity that is specified for a test but varies in the real world.
- h(x) is HIC, the Head Injury Criterion; more generally, this is the outcome of the test.
- p(h) is the cost or utility associated with the test outcome h (the clinical nature of injury and the outcome vary between different people even if HIC is the same, and in that sense p is an average); this is the quantity on which decisions are based.
- f(x) is the probability density function of x.

The cost p may be a true average dollar amount, including sums for the "value of life" and for pain and suffering. However, in the present state of knowledge, p is likely to be something simpler, such as the probability of death at a specified value of h.

Functions p(h) and f(x) are difficult to determine empirically, but estimates have been published, and were used by Hutchinson et al. (2012). For example, the probability of death as a function of HIC is included in Figure IV-10 of NHTSA (1995). A possible method of determining p(h) is to subject an instrumented headform and a dead human head to the same impact conditions; HIC is obtained from the headform, and physical damage (and hence p) is obtained by expert examination of the dead human head and expert assessment of the effects there would be in life of the injuries observed.

11.4.2 Average

The test takes place at some particular speed (e.g., 40 km/h), and h is observed. On the basis of theory, that is taken to imply some function h(x) at other speeds. The average cost is then given by the following integration.

$$Av(p) = \int p(h(x)).f(x).dx$$

The following puts this equation into words.

- Consider all conditions (in this example, all speeds of impact, x).
- Assume that the relative frequency of each condition is known. (f(x) specifies the relative frequency.)
- On the basis of a test result in one condition and a theory, work out what the test result would be in all conditions. (h(x) is this function.)
- Then convert each of these to a cost (that is, a number representing how bad it is). (p(h) is this function.)
- Use the frequencies of the conditions to average these costs.

Locations on the car differ in how safe or unsafe they are, and this equation refers to any particular location on the car. However, it may be desired to average over the whole car. Indeed, there is an equation that does that, very similar in principle to the equation above, in Hamacher et al. (2011).

Furthermore, pedestrians vary in their head mass and stature, and these may affect injury. Thus x may not be a single quantity but instead a vector of quantities such as speed of impact, effective mass of the pedestrian's head, stature of the pedestrian, and so on. Stature of pedestrian may affect what location on the vehicle is struck. Details of elaborating the basic method in these ways are in chapter 21 of Hutchinson (2018a).

The equation given above economises on the number of tests by substituting a theoretical function h(x) based on one test result in place of empirical observations. See chapter 10 for such a theory.

Equation (1) of Kanianthra et al. (1993) is similar to that above, but it was developed in the context of car-to-car side impacts. There are three main differences. (a) Kanianthra et al. envisage testing in any set of conditions that is of interest, rather than using a theory to generalise from a test result to other conditions. (b) Kanianthra et al. average the quantity that is found in the test, rather than converting it to a cost or utility. (c) And they consider that crashes might vary in a number of ways (speed, impact location, impact angle), rather than only in speed.

Table 11.1. Example of calculating Av(p). A discrete distribution of x is employed here. The probabilities are denoted f. There is an observed value of h at x = 40; from that, values of h at x = 20 and x = 60 have been calculated using some theory. For each h, there is a cost p.

1	2	3	4	5	6
f	x	h	h	p	p.f
0.5	20		88	10	5
0.3	40	500		100	30
0.2	60		1378	500	100

11.4.3 Example of calculation

Table 11.1 is an example of the mechanics of calculation.

- Instead of a continuous probability density function for f(x), there is a discrete distribution over three categories. It is supposed that three values of x (in column 2) occur with probabilities (column 1) 0.5, 0.3, and 0.2, respectively.
- Column 3 of the table shows the single value of h that was observed experimentally, at x = 40.
- Column 4 shows the values of h determined theoretically. Here, we choose x to be v and h to be HIC, and assume that the exponent n = 1.
- Column 5 shows the costs (disutilities) associated with the respective values of h (indicative round numbers here, but for a real calculation they could be determined on the basis of data).
- Finally, column 6 shows the products p.f, the total of which is Av(p) = 135.

This is only a demonstration of how the calculations are done, and the units of x and p are not stated, as they are not relevant for such a demonstration. However, 40 km/h is a common speed in pedestrian headform impact testing (see section 9.2). Note that if the method here were really to be linked with pedestrian impact testing, the angle of impact would be taken into account. In general-purpose testing, impact is usually normal to the surface (that is, at a right angle, 90 degrees). But that is not so for pedestrian headform testing. If the speed of impact is x and the angle between the direction of impact and the surface is θ, it would usually be assumed that this is equivalent to a normal impact at speed $x.\sin(\theta)$.

11.5 Discussion

11.5.1 Possible interaction of design and speed

A test protocol specifies a speed at which the test shall be conducted. The decision about the speed presumably takes into account both the many low-speed crashes and the high-speed crashes that are fewer in number but carry a much higher risk of death or serious injury. The test result is an indication of level of risk. More specifically, the result permits comparison of one model of car with another. Even if a test procedure were inaccurate as regards absolute level of risk, it might nevertheless be very useful if it provided a fair method of comparing different models of car.

Thus the question arises, if one model of car performs better than another in the test, does it also perform better in a similar test conducted at a lower speed, and in a similar test conducted at a higher speed? In statistics and many other fields, lack of consistency in this respect would be referred to as "interaction" between car design and speed in their effects on test performance (protectiveness).

Such interaction is possible. Suppose that car model A gives rise to a lower HIC than car model B at the standard test speed, but the bonnet of A is close to bottoming out whereas there is spare space available for further deformation under the bonnet of B. Then at a higher test speed, model A is likely to be much worse than at the standard speed, whereas model B will be only a little worse, and model A may now give rise to the higher HIC. For some generalised discussion of interaction, see section 12.6.

In principle, calculation of Av(p) permits a relatively poor low-speed performance that worsens only slightly with increasing speed to be balanced against a relatively good low-speed performance that unfortunately worsens sharply with increasing speed. But there are substantial practical difficulties: the function h(x) is very poorly understood in the case of bottoming out, and the function p(h) is very poorly known in the case of the very high values of h that occur.

11.5.2 Application to integrated assessment of primary and secondary safety

Probabilities f(x) specify how common are bad conditions, and the function h(x) specifies the effect of bad conditions on the object under test. Both f and h may change. Improvements to braking systems or tyres, and new technologies such as autonomous braking, may prevent some accidents and substantially reduce the impact speeds of others: there would be a change in the distribution of speeds, f(x). This would be described as an improvement of primary safety. Change to the design of the vehicle bonnet and to the stiff structures underneath are what affect the impact test result and thus h(x). This would be described as an effect on secondary safety.

As an example of integrated assessment, consider the example in Table 11.1 again. But now suppose that when x is 40, h is 550, which is a little worse. Corresponding to x = (20, 40, 60), h is predicted to be (97, 550, 1516). The costs p might be (12, 120, 600). Now suppose that the probabilities f change also, and are now (0.7, 0.2, 0.1). The sum of the three values of the product p.f is 8.4 + 24 + 60 = 92.4. That is lower than the total of 135 in Table 11.1: the change in the distribution of x has (in this example) more than compensated for the increase in h.

Calculation of Av(p) depends on both f(x) and h(x), and thus permits the integrated assessment of both primary and secondary safety features. There have been several papers on this in recent years, for example, Hutchinson et al. (2012) and Edwards et al. (2015). (There is no suggestion that secondary safety requirements should be relaxed for cars with good primary safety. Rather, it is envisaged that when improved primary safety becomes common in new cars, cars that lack those features should be subject to tightened secondary safety requirements.)

11.5.3 Some similar ideas

To me, the strategy in papers by Ferenczi et al. (2015) and Wimmer et al. (2015) appears similar to the approach I am taking in this book.

There are substantial differences. Ferenczi et al. and Wimmer et al. aim for much higher accuracy than I do, and they presume much better and more detailed information is available. Both in respect of the attempted avoidance of accidents and the moment-to-moment progress of the impact of a human, I seek a simple description. In contrast, at both stages, Ferenczi et al. and Wimmer et al. seek to be exact and realistic.

Ferenczi et al. and Wimmer et al. use the term "tool chain" to describe their sequence of calculations. In the case of conflicts between vehicles and pedestrians, this has components as follows.

- Simulation of pedestrian crossing scenarios. It is envisaged that millions of crossings of the road might be simulated. Details are not given. The vehicle may have AEB, though details of its operation are not given. The

simulation is sufficiently realistic that false positive operation of AEB can be quantified.
- Multibody simulation of pedestrian impact. This simulates the pedestrian's movement from first contact with the vehicle. Typically, first contact will be between bumper and lower leg, and the pedestrian will rotate and the head will strike the bonnet or windscreen.
- Calculation of injury proxies using finite element simulation, or approximations that are quicker to calculate. This refers to calculation of (for example) HIC from details of the head movement (speed, direction, point of impact) and details of the vehicle construction.
- Conversion of the injury proxies to probabilities of different severities of injury.

The term "virtual test system" (VTS) is used by Li et al. (2016) for a sequence of calculations that appears to me to be rather similar. This includes multibody impact simulations covering the real-world variation in impact configuration. Impact configuration here refers to a combination of impact speed, pedestrian stature, pedestrian gait, and pedestrian walking speed. The VTS also includes data on the relative frequencies of the various impact configurations.

For car occupants, White et al. (1985) reported on results of a sequence of calculations of cost from some vehicle design variables and some proportions of different types of frontal collision.

11.5.4 Equivalence between impact speed and test result

From section 10.5, the ratio of the change in HIC from a one per cent reduction in impact speed to that from a one per cent reduction in the HIC observed in a test is (4n+1)/(n+1). This is between one and four, and is 2.5 if n is 1.

11.5.5 Frailty

The frailty of the person struck is important in determining the outcome. It was not considered in section 11.4.2: frailty is typically seen as outside the scope of the testing context, as a process of averaging over people occurs in the construction of the p(h) function. (I am using frailty in quite a broad sense to refer not only to weakness but also to other reasons for poor outcome from a given physical input.)

If, on the other hand, it were thought that the distribution of impact speeds f(x) were different for people of different frailties (of different ages, for example), then it would be necessary or desirable to represent frailty explicitly in the equation.

11.5.6 Extensions

Chapters 21 and 22 of Hutchinson (2018a) deal with two supplementary lines of enquiry.

- In section 11.4.2, only one variable (speed) varies in the population of accidents but is the same for all tests. Chapter 21 of Hutchinson (2018a) considers what the process might look like if there are several such variables. This arises quite naturally in the context of testing of pedestrian safety, because some procedure of aggregation or averaging is needed to convert from test results (each referring to a location on a car's front) to a summary score for the model of car.
- There is a great deal of testing conducted of objects or people, in many different contexts. I have come across a few suggestions of procedures that seem similar to measure-generalise-cost-average. Some have been mentioned in this chapter, and there are others in chapter 22 of Hutchinson (2018a). It seems possible to me that there could be much more such research that I am unaware of.

12. Six issues in the conduct and interpretation of road accident research

12.1 Introduction

Theories in this book suggest that various input variables are likely to affect certain output variables. Many empirical studies of road accidents have demonstrated other relationships between variables. And you may have ideas about road accidents and want to compare them with data. For one reason or another, then, relationships are examined. Quite often, that is reasonably straightforward. But there are a number of features of road accident data, or of data analysis methods, that complicate matters, and which are worth collecting in this chapter. For the most part, they are ones that I have given some attention to myself --- someone else would select other issues to highlight.

A dataset of road accidents typically consists of records of many individual accidents. The record of an individual accident consists of many variables. These variables may refer to the accident (e.g., time, date, and location), to a vehicle driver (e.g., age, sex, driving licence status), to a vehicle (e.g., make, model, year), or to a person injured (e.g., age, sex, severity of injury). In most jurisdictions, the most important such dataset is derived from police reports of accidents; these may rely on police attending the scene of the accident, or on a driver reporting the accident to the police subsequently. In many jurisdictions, only injury accidents (i.e., those in which at least one person was injured) are analysed.

Important types of analysis include the following.

- The number of a particular type of accident that occur.
- The relative numbers of particular types of accident.
- The proportion of people injured who are killed.
- The proportion of people injured who are seriously injured. ("Seriously injured" includes those who are killed, as well as those whose injury is described as serious rather than slight.)
- Changes over time in the numbers and severities of accidents.
- Changes subsequent to a road safety intervention in the numbers and severities of accidents

The statistical methods employed are often similar to those in other fields of study.

Coming now to the specifics of this chapter, the titles of six sections are as below. The type of point being made is slightly different in each case, and is summarised.

Multiplicity of statistical hypothesis tests. Aim: a warning about statistical hypothesis testing.

Greater variability than the Poisson distribution. Aim: to warn against making a certain assumption when doing a statistical hypothesis test.

What place for randomised trials in road safety? Aim: to give a balanced view of the pros and cons of an important strategy of research that, despite its advantages, is not very often employed in road accident studies.

Interventions to improve drivers: Is an effect on offences any evidence of an effect on crashes? Aim: to demonstrate that this question has not yet been convincingly answered.
A model of how interaction of two variables may occur. Aim: to suggest how to model (and perhaps explain) an interaction that might be seen in data.
Low effectiveness may be cost-effective. Aim: to point out that a cheap intervention of low effectiveness may possibly be cost-effective.

The chapter concludes with a short discussion section.

12.2 Multiplicity of statistical hypothesis tests

Suppose we count the number of crashes before and after a speed limit reduction on some roads. Isn't it then easy to test for a change? Suppose we regress the probability of the driver being killed on variables like car size, driver age, and speed limit. Isn't it then easy to test for effects of the several variables?

Yes, it is easy. However, the sheer number of similar statistical tests, carried out because statistical software makes it easy, often creates difficulties. Perhaps you test for an effect of speed limit reduction or of car size (for example) in 20 different ways (different subsets of crashes, perhaps). It is not clear what the set of results means if you have tested for an effect 20 times.

Some of the variations that might need to be considered when counting the number of crashes are as follows.

- Variations of the independent variable. For example, if two technologies are presumed to be similar, should both be combined in an analysis of their effect?
- If an independent variable has three or more ordered categories, a choice is available to specify them as categorical or as numeric with a linear effect.
- In a context where several independent variables might be included as covariates, which should be included? Should combinations be separately coded, to allow for interactions?
- Variations of the dependent variable. For example, should fatal crashes be contrasted with nonfatal crashes, or should serious crashes be contrasted with non-serious crashes?
- Variations of the type of crash, and of the category of person injured.
- What severities of crash should be specified?
- What time period should be specified?
- A choice may be available concerning the level of geographical aggregation of the data.
- If a before period is being compared with an after period, should a gap be allowed between these to exclude any transient effect of a change?
- In the case of a before-after comparison, should there be a control group?
- Even after making all these decisions, there are probably several alternative statistical tests available, differing in the details of the assumptions and calculations required.

It is sometimes possible to make an adjustment to the significance level because of having performed numerous different tests. However, even the appropriateness of this might depend on the purpose the statement about statistical significance is intended to serve. In particular, many people who employ statistical tests seem to do so in the belief or hope that statistical tests give an indication of the strength of evidence in the data for a hypothesis --- and it is very doubtful whether that is really the case. Statistical tests, others would say, can never go further than rejecting or failing to reject the null hypothesis.

The problem here specifically concerns the validity or otherwise of the p-value generated in statistical testing. My opinion is that the understanding of road accidents and the improvement of road safety are quite poor, and that it is often appropriate to approach an accident dataset in an exploratory spirit. A lot of independent variables, a lot of dependent variables, a lot of possible subsets of data --- these help us understand. But data exploration often means that statistical testing is difficult. In the present state of knowledge, data exploration is usually more important than statistical testing.

12.3 Greater variability than the Poisson distribution

12.3.1 Introduction

The point to be discussed here is that the year-to-year variability in the number of road accidents is larger than implied by the commonly-adopted assumption that the number of road accidents has a Poisson distribution (Hutchinson and Mayne, 1977).

It is often wished to compare two counts of road accidents --- for example, the number before some change was made to a road junction or to a set of road junctions, and the number after the change. Consequently, the size of the difference between two counts is interpreted relative to the estimated size of the random variation associated with that difference.

- When dealing with small numbers of crashes, it is appropriate to assume the number has a Poisson distribution. One of the consequences of this is that if the expected number of crashes (e.g., in an area, or to a group of people, or to a fleet of cars) is 10, for example, the standard deviation will be the square root of 10, that is, about 3.
- But when dealing with large numbers of crashes, this is not appropriate. If the expected number of crashes (e.g., in a city) is 10000, the standard deviation would be the square root of 10000, which is 100, if the Poisson distribution were a valid assumption. But this assumption is grossly wrong: empirically the variation is often found to be appreciably greater.
- I do not know exactly what number is small enough for the Poisson distribution to be a valid assumption, but I would be reluctant to make this assumption with 50 or 100 accidents.

The reason for the extra variability is poorly understood, but it probably stems from year-to-year variations in such things as the amount of traffic, deliberate interventions in the road and traffic system to make journeys quicker or safer, alcohol consumption, enforcement of the traffic laws, weather, and the reporting of crashes.

The extra variability means that, if the annual crash numbers are large, it is likely that chi-squared tests conducted on the crash numbers are not valid.

A good response to this problem is to disaggregate the data by year. An empirical estimate of the year-to-year variability can then be calculated, rather than having to assume it is as in the Poisson distribution.

12.3.2 Statistical testing

A statistical hypothesis test often proceeds roughly as follows.

1. We state a null hypothesis. For example, that the number of crashes in a period after a change will be 90 per cent of the number of crashes in a period before the change.
2. Using the observed data, we work out what we would expect the data to look like if the null hypothesis were true.
3. Because of chance variability, the data will differ somewhat from the expected pattern even if the null hypothesis is true. We measure how far the data is from the expected pattern.
4. We work out the probability of the data being at least that far from the expected pattern, on the assumption that the null hypothesis is true.
5. If that probability is sufficiently low (e.g., less than 0.05), our conclusion is that the null hypothesis must be rejected.

Step 4 needs to use some measure of how much variability there is in the data.

- Often, this is estimated on the basis of the data.
- An important test, the chi-squared test, does not need to do that, but instead uses the variability that would be present if certain assumptions were true.

Specifically, the chi-squared test assumes that if the expected number of events (e.g., accidents) is n, the variability (in the sense of the standard deviation) is the square root of n. In the case of road accidents, this is sufficiently closely correct if n is small (e.g., 10 accidents). But there is good evidence that this is inaccurate if n is large (larger than about 50 or 100). That means the chi-squared test is quite likely to give a wrong answer if the relevant number of accidents is more than about 50 or 100.

Some papers have considered the variation from one day to another (similar) day, and others have considered variation in a yearly total (Satterthwaite, 1976; Hutchinson and Mayne, 1977; Smith, 1982; Nicholson, 1985; Long and Hutchinson, 2008). In addition to empirical demonstration, it is plain that every year differs in important respects (such as amount of traffic) from every other year, and so it is sometimes taken for granted that the Poisson assumption is inappropriate, and the important question is the size of the inaccuracy of the Poisson distribution. Then some other distribution is used instead, often the negative binomial distribution.

Regarding statistical testing, the consequences of excess variability are serious when studying broad classes of crashes (e.g., many crashes are potentially affected by an area-wide speed limit reduction, or by mass media campaigns). Firstly, the increase of variability reduces the power of statistical tests. Secondly, variability is unknown and has to be estimated from several years' data. Many statistical tests are based on similar assumptions to the Poisson distribution and are no longer valid (e.g., the usual forms of chi-squared tests). When fitting a model, the excess variability will show up as an increased standard error of the quantities estimated. As an example, Irvine (2004, pp. 40-41) was predicting a number (quarterly serious injuries) that was approximately 700, and gives standard errors calculated using a negative binomial model and using an (inappropriate) Poisson model; the former were 70 per cent greater.

12.4 What place for randomised trials in road safety?

For more details, see Hutchinson and Meier (2004).

12.4.1 Introduction

It seems likely that many researchers in road safety have felt dissatisfaction over how methods in our field compare with those in some other fields. Specifically, randomised experiments are rather rare in road safety.

Things sometimes get changed (e.g., the speed limit might be reduced from 60 km/h to 50 km/h), and people want to know what the effect was. The method that might be employed is to measure the situation before the intervention, measure it afterwards, and make a comparison. To be careful, this before-after comparison might also be made at some other place where the change had not been introduced. And, better still, the before-after comparison could be made at several places where the change was introduced, and at several places where it was not. What could possibly be wrong with such a procedure? Unfortunately, biases can easily creep in. A defence against biases that is popular in medicine is the randomised controlled clinical trial. If allocation of experimental units to treatment or control groups really is random, then it has not been affected by anything capable of generating a bias.

An important type of bias is regression to the mean. There may be a tendency for units that appear to have the problem (e.g., accidents) to a severe degree to be allocated to the treatment rather than the control group. (For example, road sections that are observed to have a high accident number or rate may be deliberately selected for treatment.) Part of the reason these units appear to be problem cases is mere chance. After treatment, there appears to be an improvement, but this is because they were not really problem cases to begin with. The phenomenon is described in the following words at p. 492 of *Research on Road Traffic* (Road Research Laboratory, 1965).

> "At any site the number of accidents will, by chance factors alone, vary from year to year.... In deciding whether or not a change is to be carried out it is usual to study the past accident record; when there are more accidents, there will be a greater chance that the scheme will be sanctioned than when there are fewer accidents. It follows that a

> particular improvement is more likely to be carried out after a period with a chance high number of accidents than after a period with average or a chance low number of accidents. After the change has been carried out, however, there is no reason to expect the chance high frequency of accidents to continue; there is an equal chance that they will be above and below average (a different average if the change had any effect). This means that there will, on the whole, be a tendency for there to be a lower frequency of accidents after than before a change, even though the change had no effect."

Tamburri et al. (1968) also made this point. Outside of a research context, and if it can be accepted that evaluation of the effect of treatment will be very difficult, a high number of accidents might be a criterion for treating a site, as in many "blackspot" programmes.

A randomised experiment might be conducted as follows.

- Specify the dependent variable (the outcome) of interest.
- Identify the unit to which the intervention is being directed. For example, the units might be people. In a transport example, the units might be intersections, roads, cities, etc.
- Define all the units of interest (e.g., sections of road) that are eligible to participate. It is permissible for criteria for eligibility to refer to the number of recent accidents: eligibility for entry into the randomisation process is very different from allocation to the treatment group.
- Randomly allocate each eligible unit to either the treatment group or the control group. Notice that this allocation is not related to the condition initially (for example, the number of crashes per five-year period).
- Measure the present condition of each unit --- the number of crashes, for example.
- Apply the intervention to the units in the treatment group, and do nothing (or nothing significant) to those in the control group.
- Conceal, both from the people participating and from the researchers who are evaluating the outcomes, which units are in which of the groups.
- Measure the condition of each unit again, that is, after the intervention has taken effect. This might again be the number of crashes per five-year period.
- The change of each unit is now known. The changes in the treatment group can now be compared with the changes in the control group. If there has been traffic growth, allowance can be made for this in making the comparison. It is likely that any statistical tests will have been specified in planning the experiment.

Many research projects of a purely longitudinal or a purely cross-sectional type certainly are carried out, but the quality of evidence from them is widely regarded as poorer than that from a control/treatment before/after comparison.

12.4.2 Examples

Randomisation and treatment of units other than individual people is rare, but does sometimes happen. Rausch et al. (1982) randomised taxi-cabs, and Retting et al. (2002) randomised intersections. Helliar-Symons (1981) evaluated yellow bar transverse carriageway markings at the approach to a roundabout. The bars decrease in separation as the roundabout is approached, creating a visual impression of speeding up, unless the driver reacts properly by slowing. Helliar-Symons examined whether this had had any effect on crash rates. Whilst not explicitly stating that assigning sites to test and control groups was wholly random, Helliar-Symons did avoid using crash record as a selection criterion, because of the problem of regression to the mean.

For further examples, see Hutchinson and Meier (2004).

12.4.3 Discussion

There is an influential body of opinion that says that the only valid way of finding out what works is randomised experimentation. Hutchinson and Meier (2004) confirmed what others have said, that randomised experimentation is very rare in transport and transport safety. Have researchers therefore been wasting their time for the past 50 years? Hutchinson and Meier felt not, because of the real practical difficulties with randomised experimentation, the principled objections to randomised experimentation, and the merits of conventional forms of research. (Principled objections referred to issues around standardisation of the treatment, standardisation of the circumstances for the treatment, and transferability of conclusions from one place to another. In road safety applications, and in social settings more broadly, it is more likely than for example with drug trials that these are matters of concern.)

The opinion of Hutchinson and Meier was as follows.

- Randomised experimentation does generate uniquely valid and convincing evidence. This is not some sort of con-trick by snake-oil salesmen.
- But the objections cannot be dismissed out of hand. The enthusiasts for randomised experimentation have not answered them comprehensively, they do have substance. The practical difficulties are real, too.
- Consequently, randomised experimentation should be considered more seriously than it usually has been in the past. It is likely that in most instances it will be rejected, either because of principled objections or impracticability, and some methodology of "lower quality" chosen instead, but that will not be known beforehand.
- There are many questions that randomisation does not give the answers to --- what outcome variable to choose, what summary statistic to calculate, what statistical test to perform, and so on. Enthusiasts will say of course it will not answer these, as they are not the questions it is addressing. That reply is fair, but raising such questions does dent the credibility of the more extreme claims about the usefulness of randomisation.

12.5 Interventions to improve drivers: Is an effect on offences any evidence of an effect on crashes?

For more details, see Kloeden et al. (2008).

12.5.1 Introduction

There are often far too few accidents to give good guidance about what conditions are safer than what other conditions --- there is so much random variation in accident numbers that the true message can easily be hidden. To some extent, it might be possible to use behaviours as proxies for accidents: a reduction in some type of bad behaviour might be taken as an indication that accidents are probably reduced also. It would be useful if driving offence information could be added to the totality of evidence --- specifically, with regard to the effects (if any) of intervening with the driver to try to reduce their likelihood of crashing.

However, there is doubt about whether it is right to do that --- concerning driver improvement studies, an effect on offences but not on crashes is quite a common finding in the literature, even in studies using randomised trials and therefore more credible. This was the general pattern found in the review by Struckman-Johnson et al. (1989), which covered studies that reported on both crashes and offences and also employed a good methodology, including randomised allocation. The types of treatment in those studies included behaviour analysis interviews, warning letters, driver improvement meetings, individual counselling, mailed pamphlets and self-test, and defensive driving courses.

A possible explanation of the contrast between offences and crashes seems to be that behaviours targeted by different interventions are more tightly focussed on offending than on crashing (Peck, 1976; Struckman-Johnson et al., 1989). For one thing, crashes may be the fault of the other driver.

12.5.2 Discussion

Kloeden et al. (2008) considered that two alternatives are plausible.

- One is that an intervention has an effect on crashes that is in the same direction as the effect on offences, because the attitudes and behaviours that are affected are factors in the occurrence of both crashes and offences, but the effect is quantitatively smaller because it is diluted by randomness.
- The other is that the intervention has no effect on crashes because the aspects of behaviour that are being affected are not relevant to crashes.

Thus, unfortunately, at present it is uncertain whether studying driving offences (in the context of an intervention intended to improve drivers) is relevant to road safety, or is irrelevant to that.

A possible way forward is disaggregation of crashes and offences, including disaggregation according to how they come to police attention. It might be that features of some types of crashes are similar to those of some types of offences, and different from others.

The opinion of Kloeden et al. was that it would be unsafe to take a reduction in offences as evidence for a reduction in crashes. When disaggregated offence data is available, it might be possible to argue that some particular type of offence is tightly linked (for example, without being subject to police discretion) to some particular type of behaviour that in turn is tightly linked to some particular type of crash. However, any such argument would need to be made cautiously and carefully.

One might wish to know whether various aspects of driver personality and demographic characteristics (age, sex, driving experience) affect both crashes and offences, as it seems quite possible that personality may affect attitudes and behaviours that are factors in the occurrence of both crashes and offences. This has not been considered above --- instead, the variable of interest has been whether or not a driver improvement intervention occurred. A conclusion about the attitudes and behaviours that may be affected by the intervention (and which may, in turn, affect crashes and offences) would not necessarily apply to the attitudes and behaviours that may be affected by driver personality (and which may, in turn, affect crashes and offences). In addition, the implications (if any) for straightforwardly predicting future crashes from past crashes and past offences are not clear.

Barraclough et al. (2016) review studies of the relationship between crashes and traffic offences. At p. 20, they write as follows. "Generally the relationship between crashes and traffic offences is not strong. The relationship presumed to be present between these variables may in fact be rather tenuous, or in many instances the associations detected may actually reflect other elements, such as exposure to the road. The weakness of the relationship between these variables suggests that the effectiveness of using traffic offences as a proxy for crashes in road safety studies is very limited".

12.6 A model of how interaction of two variables may occur

For more details, see Hutchinson (2007, 2012).

12.6.1 Interaction between threat and driving-related self-esteem

When analysing data, "interaction" of two independent variables has a specific meaning.

- If the second independent variable has the same effect whatever category of the first independent variable we are referring to, there is said to be no interaction between the independent variables.
- Interaction refers to different effects of the second for different categories of the first.

- It might even be that effects of the second are in opposite directions for different categories of the first.

Some notation and symbols will be used to clarify this in the first paragraph of section 12.6.2.

Government often wants to get social and health messages over to its population, and thereby change behaviour. There is a wide range of opinion about the effectiveness of mass media. Some people think that advertising and education campaigns will not usually improve driver behaviour. The abstract of the article by Lewis et al. (2007) begins as follows: "Threatening advertisements have been widely used in the social marketing of road safety. However, despite their popularity and over five decades of research into the fear-persuasion relationship, an unequivocal answer regarding their effectiveness remains unachieved." See Atkin (2001, pp. 31-33) for discussion of reasons why campaigns fail. The review by Lund and Aarø (2004) is quite pessimistic about preventing accidents by changing attitudes. According to Strecher et al. (2006, p. 35), "One-size-fits-all mass media interventions that run independently of other strategies have demonstrated little or no behavioural improvement."

An idea called Terror Management Theory (TMT) is interesting in providing a unified explanation of two things.

- Threat appeals can increase risky driving or risky driving intentions, that is, produce an effect in the unexpected and undesirable direction.
- Threat produces opposite effects in different people.

The key feature of TMT is the account it provides of the interaction between the mortality salience (MS) evoked by a threat appeal and driving-related self-esteem (DRS) in their effect on risky driving or risky driving intentions. This account is summarised in Carey and Sarma (2011), but it is unnecessary to go into details here.

Of course, it is often expected that threat appeals will reduce risky driving, and this expectation is sometimes realised. An effect in this direction is not incompatible with TMT, as it might occur (for example) because conforming with social norms is a psychological defence mechanism, and a means of conforming is by driving safely. TMT does, though, predict that in people for whom driving is linked to their self-esteem, threat appeals will increase risk-taking. Having in mind a clear falsifiable theory, such as TMT, helps greatly in both planning an experimental program and interpreting the results. Even better would be to have several theories that make different predictions in different circumstances.

12.6.2 Additivity followed by nonlinearity

A common notation is to let y_{ij} be the dependent variable when category i of the first independent variable accompanies category j of the second, and A_i and B_j be quantities associated with specified categories of the two independent variables.

- Interaction would refer, for example, to y_{11} - y_{12} being different from y_{21} - y_{22}.

- And y_{11} - y_{12} might even be different in sign from y_{21} - y_{22} (i.e., one difference is positive and the other negative).

The absence of interaction means that $y_{ij} = A_i + B_j$. (Both y_{11} - y_{12} and y_{21} - y_{22}. are B_1 - B_2.) The A's and B's are parameters of the model that are estimated from the observed y's.

The possibility of interaction between MS and DRS provides an opportunity for suggesting a model for interaction that might be both relevant in this specific context, and of considerably wider application. As introduction to this, note that while a main effects model without interaction might be written as $A_i + B_j$, this tends to hide the two-stage nature of what is going on: there is combination of effects of two variables, followed by conversion of the result to the observed variable by linear dependence.

When no other explanation of interaction is comes to mind, it may be worth considering additivity followed by nonlinearity (Hutchinson, 2007): quantities derived from the two factors combine by addition (or subtraction), and then the dependent variable observed is a nonlinear function of the result. Addition (or subtraction) followed by nonlinearity would imply the following model.

$y_{ij} = a + b.f(A_i + B_j)$

where f is some function, the nonlinearity of which is the source of the observed interaction. The function could even be U or inverted-U shaped, in which case effects might reverse in sign.

It may be quite difficult to fit this model to data, but this is not sufficient reason to reject the idea.

Section 11.5.1 noted that it is possible for the bonnet of one car to be less injurious to pedestrians than another at a certain impact speed, but the second car to be less injurious than the first at some different speed. The source of this interaction is that injuriousness in a nonlinear function of bonnet stiffness.

12.6.3 An alternative explanation of the interaction between mortality salience and driving-related self-esteem

A straightforward way of generating an explanation of the interaction between the mortality salience (MS) evoked by a threat appeal and driving-related self-esteem (DRS), in respect of their effect on risky driving or risky driving intentions, is as follows.

- In the absence of an interaction of MS and DRS, there would be no hesitation in saying these variables have effects that are additive.
- To explain the interaction while preserving the simple idea of addition, it may be hypothesised that the total (T) is not directly observed, but instead the observed dependent variable is a nonlinear transformation of this.
- Specifically, the dependent variable (risky driving, or risky driving intentions) may be high when T is low, lower when T is intermediate, and high when T is high (i.e., a roughly U-shaped function).

This mechanism is a step forward. A further step is to address the question, "If the dependence on T is U-shaped, what might T be?" One possible suggestion is arousal. It might be that (a) in an experiment about driving, people with high DRS are more aroused than those with low DRS, (b) threat is arousing, and finally (c) both excessively low and excessively high arousal lead to increased risk-taking (possibly because of impaired judgment or possibly deliberately).

In the experiment of Carey and Sarma, DRS was measured and MS was dichotomous. That is better than having two dichotomous variables, but it is probably not sufficient for the data to support one theory rather than another, especially since no-one low in DRS was included in the experiment. To distinguish between one theory and another, some more complex experimental design seems necessary, e.g., 3 × 3 or 2 × 2 × 2.

12.7 Low effectiveness may be cost-effective

Wundersitz and Hutchinson (2012) were particularly concerned with the question of whether mass media campaigns can improve road safety. They felt that from decades of research of varying quality, a clear result has not emerged, and that this strongly suggests that mass media campaigns do not have a large effect on safety. (See also section 12.6.1.) But it remains possible (but not proven) that there is a small saving of crashes and injuries and that advertising is consequently cost-effective. The uncertainty results from the combination of two things.

- Advertising is very cheap per person reached and hence even a small effect may be sufficient to represent good value for money.
- There is a desire to measure reductions in crashes directly, but the variability associated with estimates of crash reductions is sufficiently large that both zero effect and a small effect are compatible with the data.

I do not think it is necessary for there to be statistically-significant evidence of effectiveness before a safety measure is implemented. Implementation should be a matter of judgment based on evidence. I think evidence is good that mass media campaigns do not have a large effect, but my point here is that I also think evidence is poor that they are a waste of money.

Of course, if the small cost per person is to be justified by a safety improvement (which is small, but large enough), it is necessary that the cost really is small per person. What I have in mind is that cost per person is cost divided by number of people, and the number of people over whom the cost is spread needs to be the number of relevant people. For example, a campaign whose cost seems low relative to 1 million drivers may seem expensive if only 50 thousand of these are the type of driver for whom the campaign may have some effect.

In the hope that some substitute can be found for direct study of crash numbers, Wundersitz and Hutchinson considered (a) laboratory experiments of the social psychological type on changing attitudes, beliefs, and behaviours, and (b) measurement of safety-related behaviours. See Appendix 6 of Hutchinson (2018a) for further comments.

12.8 Discussion

Interventions are often small in scale. The number of relevant accidents per year is small, and the year-to-year variation (as it approximately has a Poisson distribution) is proportionately large. It may thus be many years before a reduction in the number of accidents can clearly be seen.

In addition, for an apparent reduction in the number of accidents to be attributed to the intervention, there needs to have been no other change that might have been responsible. But changes are occurring all the time --- one-off changes, and trends that last years or decades.

Thus evaluation of interventions is difficult for some quite widely-appreciated reasons. The issues in sections 12.2 - 12.7 are not as widely known, but they increase the difficulties. That may mean that conclusions (about whether a genuine improvement in safety occurred, or did not) are controversial. Thus it is important to look at data with the help of common sense and apply careful judgment --- and, perhaps, substantive theory.

There will be some discussion in section 13.2 of the possible use of road behaviours as proxies for accidents. Shortly after an intervention is made, when it is too early to expect a reliable conclusion from the accident data, the priority in evaluation may be to check that the intervention has not inadvertently increased danger in some way. Observations of behaviours of drivers and other road users may be useful, and theory may help us decide what those observations should be.

13. Some comments on improving road safety

13.1 Introduction

A lot of people are thinking about the future for autonomous vehicles. As I said in section 1.4, my guess is that (in the medium term) some elements of autonomous operation will be very successful, but the total package of an autonomous vehicle will not. Much of the benefit of autonomous vehicles is more likely to be 50 years in the future than 5 years in the future. Conventional road safety measures will not become unnecessary, but will continue to benefit the community for decades.

The sections of this chapter are as below.

- Advantages of theory: Road safety practice.
- Maladaptation to safety measures.
- Costs and benefits.
- Developing countries.

13.2 Advantages of theory: Road safety practice

Theory in this book is of some value in suggesting that at a late stage in the sequence of events before an impact, only a limited number of things affect outcome: travelling speed, how early danger is appreciated, reaction time, strength of deceleration.

- To improve road safety, it might be possible to concentrate on trying to affect these; we would like to have guidance from theories or data on how to do that.
- It is also natural to suggest that if an intervention is not directly aimed at affecting one of those things, the plausibility of it doing so indirectly should be examined.
- These variables are so closely linked to what happens that, if they could be measured, they might constitute indirect measures of the success of interventions.

As regards injury severity (assuming impact of the human does occur), important factors are impact speed, surface stiffness, and deformation distance available before stiffness increases greatly due to bottoming out. It is very likely that the exact part of the body impacted, and the angle, matter too --- but it is usually impracticable for general road safety study to consider such details. Some characteristics of the person injured are important (age and sex), and so may be the details of how classification of injury severity is conducted.

Much of road safety work is centred on an earlier stage, and is primarily directed at the road, the vehicle, or the driver. It is reasonable to hope that a backing of theory will both improve quality of thought about road safety, and be motivating to experts and non-experts. Indeed, there is a great variety of actions that can be taken to improve road safety. Some of these affect what I have called typical road accidents, whether via the mechanisms discussed in this book or via other mechanisms; others are directed at one or other group of unusual road accidents. (For mention of some types of unusual road accidents, see especially section 3.2.)

In addition, better theory about people (their attitudes and behaviour) and about their interactions with technology may be almost as useful as theory about road safety itself.

The public and road safety professionals often want to know what to do, and where to do it: for example, whether to spend money on a mass media campaign, whether to spend money on road improvements, whether to upgrade one intersection or another, and so on. There are often far too few accidents, I am glad to say, for these to give good guidance. To some extent, behaviours might be used as proxies for accidents, and injury accidents might be used as proxies for fatal accidents. For these possibilities, see sections 23.4 and 23.5 of Hutchinson (2018a); the discussion there is rather inconclusive, as (in my opinion) there is not much good evidence about the relationship between bad behaviours and the corresponding accidents, or about the relationship between injury accidents and fatal accidents.

Even several decades ago, when fatal accidents were much more common than now, it was recognised that accident numbers and locations needed considerable interpretation. The following quotation from (the U.K.) Department of Transport (1986, Section 4.7.1) refers to site visits conducted as part of discovering and remediating so-called blackspot locations.

> "The site visit is probably the most important element in any accident investigation apart from the historical accident data.... It is extremely unlikely that one or even two visits to the site will be sufficient. It will be necessary depending upon the subject matter of the investigation, for the accident team to drive, walk, and observe over an extended period of time. The accident team must learn to put themselves in the shoes of pedestrians, the seat of the motorists, etc., using the site, and to play the role both of someone who is, or thinks he is, familiar with the site and its condition, and of the stranger to the area. Different times of the day, daylight and dark, wet and dry, are critical features if some irregularity is to be picked up which is a contributory cause of accidents not readily identified from the printed out accident data."

I think that as there are fewer accidents now, the site visit is even more important than decades ago. My point is certainly not that substantive theory is more important than accident data and site characteristics (and common sense and expert assessment applied to both of these). Rather, it is that many tools each have a place, and theory is one of them.

13.3 Maladaptation to safety measures

Some vehicles are equipped with warning systems. For example, drivers may be warned they are following the vehicle ahead too closely. Drivers may improve their behaviour as a consequence, e.g., they may increase the gap at which they follow.

Maladaptation, in contrast, refers to a driver or other road user changing their behaviour for the worse when they perceive some safety measure is in operation. Risk compensation and risk homeostasis are similar terms. Driving faster in a vehicle that is perceived to be safer would be an example of maladaptation. Driving faster after receiving some driver training, driving faster when some road improvements have taken place, and taking more risk when wearing safety equipment would be further examples.

Speed reduction is often an appropriate safety measure. However, I feel some concern about very low speed limits in busy town centres: maladaptation by pedestrians seems possible. Pedestrians might fail to pay proper attention to traffic in streets where many people are walking and the speed limit is low. The point is that even a low-speed accident with a truck can be fatal, because of the possibility of run over.

Maladaptive behaviours are important subjects of theoretical (and practical) study not only because of their own relevance to safety, but because they are a threat to the success and usefulness of other theories about road safety. What I mean is that it may be possible to predict improved safety if something is done, other things being unchanged. Maladaptive reaction to safety measures presents us with the possibility that other things may not be unchanged, but may change for the worse.

It is controversial how important such maladaptation is. I think that some consideration needs to be given to the potential for maladaptation quite frequently, and that it is occasionally very important.

13.4 Costs and benefits

I am reluctant to make suggestions about road safety policy.

- I feel that most of the talking should be by elected politicians and the public servants they appoint. These are the people who, together, try to spend public money wisely.
- I think advocates urging a particular course of action should easily be recognised as advocates. I urge them to give additional authority to their opinions by standing for election.
- But I am mostly a researcher, and I have never been faced with choosing to spend money on one life-saving project or on another, or of choosing to spend money on a life-saving project or in some other way for the public benefit. Those are difficult and stressful tasks.

Important background to road safety policy and its implementation is that it is widely believed that road safety projects are typically very profitable, and that many possible projects are not carried out that would be profitable (but probably not as profitable as the projects that are carried out). See, for example, HRSCTRS (2004, especially pp. 47-50).

- I should explain what I mean by profitable in this context. Governments often go to a lot of trouble to put dollar values on life, on pain and suffering, and on other consequences of road accidents. Similarly, dollar values are given to things like people's time (slower speed may result in increased journey time), air pollution, and noise. Thus, from an estimate of the likely reduction in crashes that would result from a safety measure, the equivalent dollar value can be worked out. Comparison with the one-off and recurrent costs results in an estimate of profit or loss.

- I should also note that the estimate often has a lot of uncertainty associated with it. Accident numbers vary from year to year, and even after implementation it is often not clear whether a genuine reduction has occurred. (See Chapter 12 for some relevant discussion.) Experience with the effectiveness of a safety measure in other places and circumstances will not necessarily transfer to the place and circumstances being considered. Nevertheless, it is reasonable to act on the basis of an informed judgment. Criticisms at the level of a specific decision are usually inappropriate.

In the case of developed countries, there is much that is sensible about road safety policy. Improving road safety often involves spending money. The money should be spent if the future benefits are estimated to be great enough.

There are aspects of this that puzzle me, though. Perhaps it just illustrates how far I am from the mindset of the decision-makers, but I am not convinced that it is right and sensible to choose one life-saving profit-making project over another life-saving profit-making project on the grounds that the budget cannot afford both of them. Let me explain what I mean.

- Theory is simple: spend the money if you estimate that the benefits will outweigh the costs. (I am assuming that the estimate is arrived at on a proper basis, by consideration of the evidence.)
- But the financial budget is a dominant tool: it may be said that the money isn't in the budget, therefore it cannot be spent to save lives or to do anything else. The truth of that is not obvious to me in the case of government decision and government money.
- I am not arguing in favour of spending money on anything that will save lives and injuries on the roads. Rather, I am arguing in favour of spending money on anything that will give good value in terms of saving lives and injuries on the roads: it seems absurd, if the road safety improvement is estimated to be profitable, to then veto it on the grounds that the available budget does not allow the improvement to be made. Perhaps the budget is being pushed beyond the limits of its usefulness as a tool.

13.5 Developing countries

The road accident problem in developing countries is far, far, worse than it is in Australia and other developed countries. The quality of road accident data is usually worse, also, and developing countries may wish to take action without having much reliable data. Nevertheless, many improvements needed are uncontroversial, except in that they require money for implementation. Thus I will leave it to other people to suggest specifics. I can note, however, that speed reduction is a very broadly useful option for improved safety.

Some people may think that it would be sensible for developing countries to greatly reduce the maximum speed of all motor vehicles --- if necessary, by some simple and severe regulation --- and use both the police and vehicle technical means (such as power output) to achieve this. Mass public support would be desirable, too. Perhaps there should be a low speed limit everywhere. Perhaps some very low upper limit of engine capacity should be imposed on all cars, and another on all motorcycles. It may be that someone (an economist, perhaps) has already calculated an appropriate maximum speed.

A possibility is to use modern technology to monitor drivers and their vehicles --- to check, for example, that the vehicle is within the speed limit and that the driver has a valid driving licence. High-technology methods might be thought heavy-handed. But monitoring compliance with the law is, perhaps, justified by the harm that results from high speed. Drivers are fortunate that they are physically and financially able to drive, and they should not resent society at large insisting that the vehicle be driven as safely as practicable.

14. Appendix 1. List of chapters of "Road Safety Theory"

15. Appendix 2. List of chapters of "Blunt Injury and Damage: Theory to Interpret Data"

16. Appendix 3: Further results relevant to the effect of mass ratio on injury severity

16.1 Results

This continues the discussion of results that began in section 2.4.3. The ratio R is the ratio of the mass of the lighter vehicle to the mass of the heavier vehicle.

Consider crashes in which R was at least 0.6 (that is, largely car-car crashes). For each of the four crash types, there were four data points, referring to R being in the ranges .60 to .69, .70 to .79, .80 to .89, and .90 to .99. Each data point referred to the ratio of the numbers of driver fatalities in the two vehicles. If all 16 data points are included in a single regression, c is estimated to be 2.6 (standard error 0.4). Disaggregating the data, estimates were as follows.

- Head-on crashes, speed limit was at most 40 mile/h: c = 3.7.
- Head-on crashes, higher speed limit: c = 2.1.
- Intersection crashes, speed limit at most 40 mile/h: c = 2.3.
- Intersection crashes, higher speed limit: c = 2.5.

The standard errors associated with these estimates of c were in the range 0.2 to 1.0. (Locations where the speed limit was at most 40 mile/h will be referred to as urban, and locations where the speed limit was higher will be referred to as rural.)

The analysis reveals only a single quantity. It might be expressed as "If there is a 1 per cent change in relative impact speed, what is the fractional change in the probability of death (p)?", and the answer is 2.6 per cent (2.6 per cent of p, that is). No attempt is made to give different answers for different speeds.

For each of the 16 combinations of crash type and mass ratio R, this method of analysis is based on the ratio of two numbers of fatalities. An alternative analysis is given in section 16.2 below.

16.2 Analysis using a more complicated model

The analysis here is of the data for head-on crashes. Hutchinson (1977, 1982) reported results of fitting a model of injury severity to a cross-tabulation of injury severity of driver of the lighter vehicle and injury severity of driver of the heavier vehicle. In that model, a higher probability of death implies a higher probability of serious injury relative to slight injury, and a higher probability of slight injury relative to no injury. Thus the relative numbers of all severities of injury contribute to estimating how the probability of death is affected by mass ratio.

The totality of crashes was assumed to be made up of a mixture of two relative velocities. This permits the positive correlation (at a given mass ratio) between the two drivers' injury severities to be accounted for; the correlation arises because the relative velocity of the vehicles is different in different crashes but

common to the two drivers in each crash. The model is a crude approximation, but is convenient for present purposes.
Results reported by Hutchinson (1977, 1982) included the following.

- At the lower of the two relative velocities, which constitute some 84% of those in rural areas and 89% of those in urban areas, there was virtually zero probability of being killed.
- In the remaining 16% of crashes in rural areas and 11% of crashes in urban areas, the probability of being killed was about 10%. This varies with the relative velocity change of the vehicles. ("Relative velocity change" of the vehicles here means the ratio of the mass of the other vehicle to the sum of the masses of the two vehicles. Under certain assumptions about the collision, it is the change of velocity of a vehicle expressed as a proportion of the original relative velocity. See sections 2.4.2 and 7.2.)
- In view of the interest in Nilsson's power law (see section 2.2), it would be convenient to use logarithmic axes when plotting data, as a straight line will imply a power function. When this is done, the slope is found to be approximately 3.4 (rural data) and 5.1 (urban). (That refers to crashes in which the lighter vehicle was at least half the mass of the heavier, i.e., mostly car-car crashes.) As noted earlier, most vehicle occupants in the dataset were unrestrained.

Some underlying assumptions are unrealistic, and conditions today are rather different from 40 or 50 years ago, and thus the validity of this and its implications may be questioned. But the results are at least consistent with the idea that there is a strong and smooth dependence of probability of death on speed that occurs at the upper end of the speed distribution (but within the range of crashes that occur reasonably commonly). The results also suggest that if the speeds of the quite small proportion of relatively severe impacts could be brought down, the effect on the number of road deaths arising by the usual mechanism would be utterly disproportionate. (This would not necessarily apply to the appreciable proportion of present-day crashes in which injury occurs by one or another unusual mechanism.)

It might be asked whether cross tabulating the two injury severities and fitting a complicated model is really necessary: variation in probability of death can be related to variation in mass ratio without such complexity, as in Grime and Hutchinson (1979, 1982). However, results could possibly be strongly influenced (and, in a sense, distorted) by the many slow speed crashes in which death is extremely unlikely, even in the case of the driver of the lighter vehicle.

If exponents of 3.4 and 5.1 were thought to be relevant in modern conditions, three examples of implications would be as follows.

- If lower impact speeds (achieved by, for example, lower speed limits) led to velocity change being reduced by 10 per cent, the risk of fatality would be reduced by 30 per cent or 42 per cent for exponents of 3.4 and 5.1, respectively.
- In Australia at present, a large car has approximately 1.6 times the mass of a small car. Thus in a collision with an average car, the relative velocity change of a small car is about 26 per cent greater than that of a large car. Exponents of 3.4 or 5.1 would respectively imply the small car's driver

would be 2.2 or 3.3 times more likely to be killed than the large car's driver.

- For car-car collisions, the variation of number of deaths per collision with mass ratio is so weak that it cannot confidently be perceived against the background of random variability in the data under discussion, at least in the British dataset under discussion. That is, higher risk in the smaller car is approximately balanced by lower risk in the bigger car. However, a power function would mean that the balancing is not exact, and that there would be fewer deaths if cars were less variable in mass. An exponent of 3.4 would imply that for mass ratios of 1.6, 1.4, and 1.2, deaths per collision are 1.22, 1.11, and 1.03 times those for a mass ratio of 1.0. An exponent of 5.1 would imply that for mass ratios of 1.6, 1.4, and 1.2, deaths per collision are 1.57, 1.29, and 1.09 times those for a mass ratio of 1.0.

No doubt these findings are to some extent sensitive to the details of the model that was assumed, but the results nevertheless constitute evidence of a strong dependence of probability of fatality on velocity change.

16.3 Other features of this dataset

Though distinct from the issue of speed, two further features of the dataset are so important as to require mention.

First, to keep the set roughly homogeneous, the crashes analysed in section 2.4.3 were restricted to R being at least 0.6. The question may be raised of how numerically important, in respect of the number of deaths, are extreme disparities in vehicle mass. The answer is that such crashes (that is, truck vs. car crashes) are very important. Consider crashes in which the larger vehicle was at least five times the mass of the smaller. These accounted for 49 per cent of fatalities in head-on crashes where the speed limit was at most 40 mile/h, and 42 per cent of fatalities in head-on crashes where the speed limit was higher (Hutchinson, 1977, Table 5; 1982, Table III).

Second, because of greater velocity change, occupants of small cars are at more risk overall than occupants of large cars. The question may be raised whether there is any effect of vehicle mass in addition to the effect of mass ratio.

- For two-vehicle collisions in which the vehicle masses were close to equal, drivers of small cars were not any more or less likely to suffer death or serious injury than those of large cars.
- There was no effect of vehicle mass on injury severity in single-vehicle crashes.

See Grime and Hutchinson (1979, 1982). As most drivers were unrestrained, these results are not surprising (the interiors of small cars are similar to those of large cars, and the crushing characteristics of small cars are similar to those of large cars). See also chapter 8 (and especially, for relevant data, section 8.8 and Appendix 6).

16.4 Discussion

Road crashes have changed in some respects since the data analysed here were obtained. Changes include a much lower proportion of unrestrained occupants now, and perhaps deaths by unusual mechanisms are relatively more frequent. Thus it would be desirable to estimate the exponent c using a recent dataset. However, sample size might be a problem. There were approximately 30000 road deaths in Great Britain in 1969 - 1972. Even so, in the present analysis the numbers being compared were as few as, for example, 65 with 56 (head-on crashes, speed limit higher than 40 mile/h, mass ratio in the range .90 to .99) and 11 with 8 (intersection crashes, speed limit 40 mile/h or less, mass ratio in the range .70 to .79).

What has been estimated here is the effect of change of velocity, rather than travelling speed. It is thus of particular relevance to secondary safety, rather than primary safety. Reduction of travelling speed would be expected to have a stronger effect because, in addition, some crashes will be prevented.

17. Appendix 4: Equations of motion with constant acceleration

The equations in this paragraph are familiar in elementary physics or applied mathematics. See, for example, the Wikipedia article on Equations of motion. In this paragraph, the symbols s, t, u, v, and a will be used with the following meanings: s = distance moved, t = time taken, u = initial speed, v = final speed, and a = the constant acceleration. The following equations give the interrelationships of s, t, u, v, and a.

$v = u + a.t$

$s = u.t + ½.a.t^2$

$s = ½.(u + v).t$

$v^2 = u^2 + 2.a.s$

$s = v.t - ½.a.t^2$

These equations are sometimes known as the SUVAT equations because of the symbols that are usually used.

Elsewhere in this book, those symbols are used with slightly different meanings. Consider a vehicle initially travelling at speed v, that starts braking with deceleration a when it is at a distance s from an obstacle. These changes mean that v is replaced with u, u is replaced with v, and +2.a.s is replaced with -2.a.s. If the vehicle fails to stop before hitting the obstacle, the square of the speed of impact u will be given as follows.

$u^2 = v^2 - 2.a.s$

That is how the equation appears in section 5.2. Here, u is the second (lower) speed, v is the first (higher) speed, and a is considered positive even though it is a deceleration.

18. Appendix 5: Exposure (to risk) and induced exposure

18.1 Accident rates

The intention here is to give some introduction to exposure (to risk), accident rates, and induced exposure. It is based on parts of Hutchinson et al. (2009). (See also Wundersitz and Hutchinson, 2008, and section 23.6 and Appendix 7 of Hutchinson, 2018a.)

If different groups of people are found to have different numbers of crashes, should this be attributed to underlying differences in crash risk or differences in exposure to risk? When a question like this is asked, the term exposure is being used in the context of the equation *number of crashes* = *rate* × *exposure*. For example, truck drivers may have more crashes per year than car drivers because they drive more, that is, their exposure is higher.

There are a number of different varieties of exposure, and thus of rates, and similar questions may be asked of intersections having different numbers of crashes, models of car having different numbers of crashes, environmental conditions, and so on. For example, the total crashes to a group of people sharing a common characteristic may be divided by the total exposure of that group of people, resulting in a rate that is intended to be relevant to the group.

When an accident rate refers to people, the question of fairness may arise. Drivers who drive a long distance per year tend to have fewer accidents per kilometre driven than drivers who drive a short distance per year. One of the reasons is that the extra distance is disproportionately on motorways, which are relatively safe. If a group of people (e.g., the elderly) tend to drive only a short distance per year, they will tend to have a high number of accidents per kilometre. That may be attributed to the people, when it ought more properly to be attributed to their low distance driven, or to the type of road driven on. For this, which is sometimes termed "low mileage bias", see Janke (1991).

While groups having a high *number* of crashes per year can be identified from crash data alone, identification of high crash *risk* groups requires a measure of exposure. There has for decades been rather unsatisfactory treatment of exposure in road safety research, making it difficult to know just what the risks are and how effective road safety countermeasures have been. Appropriate exposure data is often not available or is difficult or expensive to obtain. "The utility of exposure data, i.e., road-use data, in road-traffic-accident research is widely acknowledged. This is so in spite of the rather underdeveloped state of exposure research throughout the world." So wrote Somers and Benjamin (1982), and Hutchinson et al. (2009) largely agreed.

Writing *number of crashes* = *rate* × *exposure* reminds us that one way of reducing crashes is to reduce exposure. For example, we might reduce the amount of travel on the roads. Governments typically influence things by the use of regulations and taxation. Taxation policy (for example, how high should the price of motor fuel be) and urban planning strategy (for example, the distances between homes and workplaces) are usually considered outside the area of the road safety specialist.

Whenever something new is found in the crash numbers, exposure is what comes to mind as the likely explanation. However, it is typically difficult to confirm or disconfirm such speculation: exposure as a concept is too indefinite, or the data on exposure is not sufficiently detailed. Some illustrations of this are in Hutchinson (2018a, Appendix 7).

Accident rates may be used descriptively. Going beyond this, in the context of people, accident rates are often thought to reflect accident causation: groups of people with high accident rates are presumed to cause more accidents than other groups. However, that might not be quite correct: Chapter 5 of this book emphasised the importance of reaction to an obstacle in avoiding or mitigating a crash, the driver who is reacting possibly being innocent of causing the crash. It thus highlights the possibility that a high accident rate may be the result either of causing a lot of accidents or of not avoiding a lot of potential accidents.

> I am sure that point has been made many times previously. For example, Catchpole et al. (1994) give some prominence to the over-representation of young drivers in accidents resulting from conflicts created by unexpected actions of other road users. Catchpole et al. ascribed this over-representation largely to difficulty in detecting or predicting conflicts early enough.

18.2 Induced exposure: A method of by-passing measurement problems

The following also is based on parts of Hutchinson et al. (2009). (See also section 23.7 and Appendix 8 of Hutchinson, 2018a.)

Exposure is difficult to define and difficult to measure. Haight (1970) identified three general strategies for dealing with the difficulty.

- To accept crude quantities such as distance driven, and eliminate confounding factors to as great extent as is practicable with the data available.
- To ignore exposure, concentrate on absolute numbers of crashes, carry out cost-benefit analyses with these, and decide on implementation on this basis.
- To manipulate crash data in such a way as to obtain "exposure-corrected" crash figures, without using any other data such as distances driven.

The third of these is known as the induced exposure approach.

As an example, consider the ratio of the number of a particular category of drivers responsible for crashes to the number of that category innocently involved in crashes. (See also section 7.3.1.) This might be called an over-involvement ratio. The amount of traffic to which this group of drivers is exposed will be reflected both in the number of times they are an innocent party in crashes and in the number of crashes they cause. The inherent danger of the group will only affect the latter, however, and taking the ratio of one to the other results (so it is hoped) in an exposure-corrected crash figure.

It was noted at the end of section 18.1 that a high accident rate may be the result either of causing or of failing to avoid a lot of accidents, and these alternatives may be very different. Similarly, the importance of reaction to an obstacle in avoiding or mitigating a crash (chapter 5 of this book) implies that being innocently involved does not equate to being passive and lacking relevant personal characteristics.

19. Appendix 6: Data on the effect of car mass on injury severity

19.1 Introduction

This follows on from section 8.8. The data discussed here is mostly from the U.S.A. For further information, see Hutchinson and Anderson (2011, 2013).

It is not controversial that, overall, occupants of small cars tend to be more severely injured than occupants of larger cars --- this is because of the greater velocity change in the smaller vehicle when vehicles of unequal sizes collide. (By small and large, I mean small in mass and large in mass.) An important question is whether, in crashes between two cars of approximately equal mass, and in single-car crashes, occupants of small cars tend to be more severely injured than occupants of larger cars.

Empirical evidence is conflicting. As expected, British data shows no effect (Grime and Hutchinson, 1979), but surprisingly American data shows a strong effect (Evans, 1991, pp. 64-77; 2004, pp. 79-82). A more recent study with South Australian data found no effect (Hutchinson and Anderson, 2011).

- One reason for controversy is that different questions get put together. Of interest here is secondary safety, not primary safety. Consequently, studies are not relevant if they fail to isolate secondary safety (e.g., fatalities per crash or per injury crash) but instead refer to fatalities per billion miles or per million vehicles.
- The main purpose of this Appendix is to draw attention to three reasons for scepticism about data from the U.S.A.

It should be noted that in many empirical studies, the speeds of the crashes were not known. If, in crashes between cars of approximately the same mass, car mass is not associated with injury severity, the simplest explanation is that neither crash speed nor secondary safety at a given speed are associated with car mass. A weakness of such studies is that this simple explanation is not necessarily the correct one: it could be that both associations exist and cancel out.

19.2 Reasons for scepticism

19.2.1 Damage-only crashes

Many American analyses include damage-only crashes in the denominator number of crashes. They are potentially misleading, in that the results will be distorted if under-reporting of damage-only crashes is different for different sizes of car.

For New York state, Milic (1972) noted an excess of property damage reports for new and/or expensive cars that resulted in an apparent decrease in severity and an increase in accident rates for those cars. Milic (Section 11) goes so far as to say that "the property damage accident reporting threshold appears to make comparisons between cars of different sizes impractical",

19.2.2 Unusual light cars

Models of car differ. It is likely that they differ in respect of secondary safety, as well as in other respects. Mass is one of the possible reasons. If one or two models constitute a large proportion of the vehicles in a particular range of mass, the data will reflect the other features of those one or two models, as well as the mass. If those features are unusual, the crash data may be unusual, too.

In U.S. datasets from the 1970's, Volkswagens and the Ford Mustang constituted a large proportion of the lowest weight classes. The Volkswagens were atypical, however, being rear-engined; furthermore, a car that is unusual, whether in size or in other ways, might be unusual in other respects --- characteristics of the drivers, how it is driven and the environment in which it is driven, the relative numbers of different types of crash, the probability of a crash being reported, and so on. The Ford Mustang also was atypical: in the words of Wikipedia, pony cars had a sporty or performance-oriented image, and received youth-oriented marketing and advertising. The overall results will have been distorted if there was anything unusual about Volkswagen and Ford Mustang crashes specifically, and it is plausible this was the case.

19.2.3 Data presentation

Some studies did something odd in the data processing. For North Carolina data, Evans (1991, 2004) chose to plot smoothed rather than raw percentages. For FARS data (Fatal Accident Reporting System), Evans and Wasielewski (1987) used an idiosyncratic statistic with the square of the number of pedestrian fatalities as the denominator.

19.3 Discussion

I do not say that the arguments above prove that the U.S. data is wrong or that there is no effect of car mass on safety, but I do say they provide good justification for scepticism.

Campbell and Reinfurt (1973) reported a strong effect of mass on injury severity in two-car collisions, even when allowance was made for the effect of mass ratio. (The data was from North Carolina; see also O'Neill et al., 1974.) The following words make reasonably clear that their view was that it was neither mass itself nor crush distance that was responsible for the apparent effect of mass: "The particular deformation characteristics of the car are largely irrelevant to the non-belted driver since the vehicle crash (whether a favourable or an unfavourable deceleration profile) is usually over before the driver hits the interior structure of the compartment. Thus, for a single car crash, interior design characteristics may be the overriding influence (given that belts are not worn)."

20. Appendix 7: Improving pedestrian protection by testing a car's front

20.1 Introduction

Section 9.2 introduced the principles for minimising the danger posed by a car's front (especially the bonnet) to pedestrians and other vulnerable road users. This Appendix continues that discussion.

Regulations and recommendations could attempt to control separately several aspects of bonnet design, instead of the global performance summary represented by the Head Injury Criterion --- surface sharpness, clearances, bonnet stiffness, stiffness of under-bonnet structure, coefficient of restitution, and damping of the bonnet. However, vehicle and component manufacturers have a great deal of expertise, and it seems reasonable to focus on overall performance and leave the method of achieving that to the vehicle designer. There may be other contexts of blunt head injury, though, in which it would be appropriate for regulations or specifications to refer directly to analogous aspects.

Routine headform testing has been carried out by the European New Car Assessment Programme (Euro NCAP) and the Australasian New Car Assessment Program (ANCAP) for some time. The tests are for consumer information purposes only: this is not regulatory testing, and poor performance will not stop a vehicle from being sold.

Lawrence et al. (2006) demonstrated several methods for improving the pedestrian test performance of two cars: a Ford Mondeo and a Landrover Freelander. These vehicles were compared with the better-performing Honda Civic. Several design improvements were suggested, most of which involved increasing clearances and reducing the stiffness of bonnet supports. Another feature of the Honda Civic was that the stiffer structures beneath the bonnet were designed to break away --- for example, the windscreen wiper motor and the brake fluid reservoir. The features of this study illustrate the progress that was being made by one manufacturer (Honda) at the time, in contrast to manufacturers that had not considered pedestrian safety as a high priority. Other references about improving the pedestrian safety of cars include Clemo and Davies (1998), Han and Lee (2003), Hobbs et al. (1985), Kuehnel and Appel (1978), Wollert et al. (1983), and Yoshida et al. (1999).

Since 1997, the impact laboratory at the Centre for Automotive Safety Research, University of Adelaide, has conducted pedestrian headform and legform testing on behalf of ANCAP, plus tests for other clients and other purposes. Ponte et al. (2013) describe this activity. See Appendix 5 of Hutchinson (2018a) for improvements that have been noted in respect of head impacts. For the Euro NCAP test method (and, in particular, the changes to headform impact procedures from 2013), see Zander et al. (2015). See Whiteside (2010) for information about seven pedestrian headform protocols using a 2.5 kg headform at 11.1 m/sec or a 3.5 kg headform at 9.7 m/sec, and seven protocols using a 4.5 kg headform at 9.7 m/sec or a 4.8 kg headform at either 9.7 or 11.1 m/sec.

There is likely to be further progress in coming years as the designs of bonnets and other relevant vehicle structures are revised. In many respects, testing protocols for regulatory and consumer information purposes will be expected to work well. For stiffness of hard structures, clearance under bonnet, and coefficient of restitution, it is appropriate for regulation to encourage design in one direction: the softer that hard structures are, the better; the greater the clearance distance, the better; and the lower the coefficient of restitution, the better. Bonnet stiffness, however, is a special case, and this will be discussed below.

20.2 Bonnet stiffness as a special case

For bonnet stiffness, as noted in section 9.2, it is not the case either that more is better or that less is better. Instead, there is an optimum: too stiff, and injury is quite likely to arise because of that stiffness; not stiff enough, and the pedestrian's head bottoms out, that is, strikes the very stiff structures in the engine compartment. The optimum stiffness succeeds in bringing the head to rest just before the very stiff structures are contacted; that is, all the clearance distance is used up. (This description is an approximation in at least two ways. Stiffness may vary with deformation distance, and stiffness may depend on speed as well as on deformation.)

However, the stiffness that is optimal at one speed will not be optimal for other speeds.

- In particular, severity of injury at higher speeds may be very bad because of bottoming out --- especially if the bonnet is optimised for quite low speed impacts, i.e., is fairly soft.
- Severity of injury at speeds lower than that for which stiffness was optimised will also be worse than necessary, as all the available clearance distance is not used.

Consider severity of injury as a function of speed of impact, with some particular clearance distance being available before bottoming out occurs. (I will not refer to any specific definition of severity, as I intend to give a valid general picture whatever definition is used.)

- Suppose the bonnet to be optimised for an impact at 40 km/h, say. At speeds of impact lower than 40 km/h, there is gradually increasing severity of injury with increasing speed, as more and more of the clearance distance is used up. At higher speeds of impact, there is sharply increasing severity of injury, as bottoming out gets worse and worse.
- Suppose the bonnet to be optimised for an impact at 50 km/h. At speeds of impact lower than 50 km/h, there is gradually increasing severity of injury with increasing speed, as more and more of the clearance distance is used up. At higher speeds of impact, there is sharply increasing severity of injury, as bottoming out gets worse and worse.

- And the following two comparative statements are fairly evident. At speeds lower than 40 km/h, severity for a bonnet optimised for 50 km/h is higher than for a bonnet optimised for 40 km/h. At speeds higher than 50 km/h, severity for a bonnet optimised for 50 km/h is lower than for a bonnet optimised for 40 km/h.
- At some speed a little over 40 km/h, the lines for the two bonnets of different stiffnesses cross over.
- At low speeds, the bonnet optimised for the higher speed performs worse: it is too stiff.
- At high speeds, the bonnet optimised for the higher speed performs better: it absorbs more energy before bottoming out occurs.

A stickler for accuracy may object that there is no way of measuring injury severity on a quantitative scale, that injury severity should be considered an ordinal variable, and that consequently it is meaningless to refer to an increase of injury severity as being gradual or sharp. I mostly agree, but the wording above is sufficient for present purposes.

I would expect the above to be approximately true quite generally. However, in any specific case there are likely to be many important details. For example, the possibilities of nonlinear stiffness and velocity-dependent stiffness may be available, though perhaps at increased cost.

According to the argument above, the line representing dependence of injury severity on impact speed for a bonnet of one stiffness may cross over that for a bonnet of another stiffness. The reason is that the bonnet of lower stiffness bottoms out at a lower speed.

- If such cross over is observed in empirical data, it may be due to bottoming out, but that is not the only possibility.
- Instead, the laws governing impact behaviour may be different for the two bonnets.
- For example, the exponent n in the class of possible laws proposed in section 10.4 might be different for different bonnets, leading to cross over.

See Appendix 9 of Hutchinson (2018a) for a suggestion about optimal stiffness when there are several speeds of impact (and therefore there needs to be some sort of process of averaging).

I understand the consequences of test speed have been controversial in the testing of motorcycle helmets. Consider a set of helmets that have passed a compulsory test at a relatively low speed, and another set of helmets that have passed both the compulsory low-speed test and an optional test at a relatively high speed.

- My opinion is that it is reasonable to be concerned that good performance at high speed may have been achieved at the expense of poorer performance at low speed.
- Becker et al. (2015) provide evidence that this has not in practice happened. They reported results of tests at several speeds of helmets from two sets as described. Average performance of the second set was better at high speed than that of the first set, and was similar at low speed.

Request

Please drive a little slower, and wear your seat belt.

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