

# **Road Safety Theory**



# Road Safety Theory

**T. P. Hutchinson**

"Road Safety Theory" was first published (on the web at  
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This version is dated 13 November 2018.

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### **What this book is about**

There is convincing data showing that a small reduction in impact speed leads to a relatively big reduction in road fatalities.

There is great interest at present in AEB (Autonomous Emergency Braking). With it, a car detects an obstacle and brakes itself, without a command from the driver.

A small reduction in travelling speed, or braking earlier by a fraction of a second, or a small improvement in strength of braking --- any of these, whether achieved by AEB or by other means, will greatly reduce road fatalities.

Safety testing of vehicles is an important part of the total road safety system. It includes AEB testing, and impact testing in which an instrumented headform (representing a pedestrian's head) strikes a car's exterior.

It is desirable for test results to be of some relevance in conditions other than those directly tested.

The above matters are dealt with in this book. They are the nearest I can get to a useful road safety theory. I am unable to provide explanations of the mistakes and misbehaviours of people on the roads.

T. P. H.

There is some overlap between the contents of this book and "Blunt Injury and Damage: Theory to Interpret Data" BluntInjuryandDamage.com, which is also by T. P. Hutchinson and also published in 2018. (And there may be similarities to papers by Hutchinson. References to these are given in the usual way.)

Roughly 30 per cent of this book is similar to roughly 30 per cent of the other. The biggest area in common is blunt head injury in the context of road accidents. Chapters 16 - 20 of this book are similar to chapters 2, 3, 4, 7, 19 of "Blunt Injury and Damage: Theory to Interpret Data".

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## Part A. Background

The first five chapters are background, or a foundation, for the remainder of the book.

1. Introduction to this book.
2. Typical vs. unusual road accidents.
3. The importance of speed: Empirical data.
4. From travelling to injury: Overview.
5. Equation for impact speed.

Section 5.4, the final section of chapter 5, gives an overview of chapters 2 - 5.

Much of the time, I chiefly have in mind "typical" road accidents, and chapter 2 describes what I mean by this. (Even so, a lot of the book is relevant to many of the unusual road accidents also.)

Vehicle speed is prominent in this book. That is because impact speed has quite a big effect on the probability of being killed. Thus chapter 3 gives a selection of evidence for this.

# 1. Introduction to this book

## 1.1 *The approach taken in this book, and the reasons*

Road safety is very much a data-driven subject, and you may consider that I have made a mistake in attempting to write a book on road safety theory. I will quickly describe the approach I am taking, and perhaps persuade you that the book is worthwhile. And I do think there is a great need for such a book. This is partly because of the many deficiencies with road safety data, and partly because of the value of theory in making thinking easier.

"Road safety theory" might mean different things to different people. What I mean by it is shown by the titles of three of the major sections of this book.

- *Emergencies: Detection and reaction.* That is, the subject is the last second or so before the vehicle strikes something.
- *Impact of the human.* Injury (or possibly death) to a pedestrian occurs when struck by a vehicle. For vehicle occupants, there is a complication, in that injury or death typically occurs not at the moment of the vehicle's first contact with an obstacle, but a fraction of a second later when the occupant strikes some part of the vehicle's interior.
- *Generalisation from a test to the real world.* This refers to a test of a vehicle (a pedestrian impact test, for example) being in specified conditions. In other conditions, as commonly occur in the real world, the result of the test would be different.

Regarding emergencies, 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. Regarding human impact, an important example is that of pedestrians struck by cars. 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.

So that's what I mean by road safety theory. There are two main reasons why the content of this book is as it is.

- 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 that is worthwhile in respect of reducing the probability of death.

- 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.

Possibly there are a lot of topics you would like to read about, but aren't here. Sorry about that, but I can only offer what I feel I know something about. There is not much in this book about the initiation or causation of the emergency (for example, whether something moved into the path of the vehicle, or whether there was loss of control), though a few comments will be made in sections 23.1 and 23.2.

A few examples of topics that you might think would be in this book, but are not, 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.)

People working in road safety would like theories about lots of things. But the past decades of research have to only a limited extent, I think, produced a body of work recognised as road safety theory. The approach 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 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) 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. (c) 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.

### 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.

### 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**

It is worth noting that there are some sections that summarise several chapters. These are as follows.

- (5.4) *Overview of chapters 2 - 5.*
- (8.7) *Overview of chapters 6 - 8.*
- (10.6) *Overview of chapters 9 and 10.*
- (13.5) *Overview of chapters 11 - 13.*
- (15.9) *Overview of chapters 14 and 15, and a look forward.*
- (20.6) *Overview of chapter 20, and a look forward.*

Some people might like to read these overviews first.

Three of the major Parts of this book are as follows.

- (Part B) *Emergencies: Detection and reaction.*
- (Part C) *Impact of the human.*
- (Part D) *Generalisation from testing in closely-specified conditions to real-world variability.*

Part A of this book is Background, and Part E is Ending and Appendices.

Part A has five chapters.

- (1) *Introduction to this book.* This includes, in section 1.6, an explanation of some specialised terms.
- (2) *Typical vs. unusual road accidents.* The theory in this book is most relevant to typical or ordinary road accidents. This chapter explains what I mean by that.
- (3) *The importance of speed: Empirical data.* Vehicle speed is prominent in this book. This is because it is widely thought that impact speed has a big effect on the probability of being killed, and thus on the number of people killed.
- (4) *From travelling to injury: Overview.* The sequence of events in typical road accidents is described.

(5) *Equation for impact speed.* The equation for impact speed if deceleration is constant is given. A model or rule, termed model [A], for how the vehicle behaves when it encounters an obstacle is suggested.

The first five chapters of Part B carry discussion of Autonomous Emergency Braking (AEB) from introduction, through modelling and testing, to examination of some empirical evidence on its effectiveness. See Table 1.1. The remaining three chapters of Part B supplement the earlier ones in several ways. See Table 1.2.

Part C begins with chapters on the movement of vehicles in collisions and the movement of vehicle occupants during a crash. Most of Part C concerns the impact of a human (e.g., a human head) with something that deforms, such as part of a car exterior or interior. See Table 1.3.

Part D has three chapters. See Table 1.4.

Part E has two chapters. See Table 1.5.

In addition, there are appendices as follows.

(25) *Appendix 1: Further results relevant to the effect of mass ratio on injury severity.*

(26) *Appendix 2: Newton's equations of motion.*

(27) *Appendix 3: Test results of Seiniger and Gail (2015) viewed abstractly.*

(28) *Appendix 4: Data on the effect of car mass on injury severity.*

(29) *Appendix 5: Improvements in the design of cars for pedestrian impacts.*

(30) *Appendix 6: Behaviours as proxies for accidents.*

(31) *Appendix 7: Some difficulties with accident rates.*

(32) *Appendix 8: Induced exposure.*

(33) *Appendix 9: Stiffness when there are several speeds of impact.*

References are listed alphabetically at the end of the book. References are usually cited because they are relevant to the specific point being made. If, instead, they are mentioned because they are more broadly relevant to the topic or to a related topic, the wording usually makes that clear.

There is some overlap between the contents of this book and "Blunt Injury and Damage: Theory to Interpret Data", which is also by T. P. Hutchinson and also published in 2018, and is listed in the References as Hutchinson (2018). Roughly 30 per cent of this book is similar to roughly 30 per cent of the other. The biggest area in common is blunt head injury in the context of road accidents. Chapters 16 - 20 of this book are similar to chapters 2, 3, 4, 7, 19 of "Blunt Injury and Damage: Theory to Interpret Data".

Table 1.1. The first five chapters of Part B. (See section 8.7 for an overview of chapters 6 - 8, and section 10.6 for an overview of chapters 9 and 10.)

The first five chapters of Part B carry discussion of Autonomous Emergency Braking (AEB) from introduction, through modelling and testing, to examination of some empirical evidence on its effectiveness.

- (6) *Autonomous emergency braking*. This chapter introduces AEB, and methods of testing AEB systems.
- (7) *Interpretation of AEB test data from a sudden challenge*. The definition and measurement of the effectiveness of an AEB system is likely to be easier if it is possible to measure the time from a challenge by an obstacle to a command for emergency braking.
- (8) *A model for AEB operation*. The implications of model [A], introduced in chapter 5, are developed.
- (9) *Interpretation of AEB test data: Testing without access to the vehicle's internal communications, and using a continuously-viewed obstacle*. This chapter adapts what is proposed in chapter 8 to the methods of testing currently popular.
- (10) *Data from AEB testing by Hulshof et al. (2013)*. Empirical data on the performance of AEB systems, reported by Hulshof et al. (2013), is discussed.

Table 1.2. Chapters 11 - 13 in Part B. (See section 13.5 for an overview of chapters 11 - 13.)

The remaining three chapters of Part B supplement the earlier ones in several ways.

- (11) *Discussion of AEB testing and the data*. Some further empirical data is examined. Several aspects of AEB testing and modelling are discussed. Some theory developed in the context of human drivers is summarised.
- (12) *How to construct your own model for a driver or a vehicle acting autonomously*. This chapter suggests some building blocks that might be useful in constructing models that are improvements on model [A].
- (13) *The effect of travelling speed on impact speed: Quantitative demonstration*. There are some straightforward calculations of what percentage reduction in impact speed will result from a 1 per cent reduction in travelling speed.

Table 1.3. The chapters of Part C. (See section 15.9 for an overview of chapters 14 - 19.)

Part C begins with chapters on the movement of vehicles in collisions and the movement of vehicle occupants during a crash. Most of Part C concerns the impact of a human (e.g., a human head) with something that deforms, such as part of a car exterior or interior.

(14) *Movement of a car in collision.* The simplest geometry of collision is sufficient for this book. This chapter is based on applied mathematics that you may have learnt at school.

(15) *Movement of a car's occupants in a crash.* This chapter concentrates on frontal impacts involving fatal or serious injury.

(16) *Pedestrian impacts: Testing a car's front.* The principles for minimising the danger to pedestrians posed by a car's front (especially the bonnet) are discussed. In effect, the bonnet should act as a cushion: there should be plenty of clearance distance under it before the stiff structures of the engine compartment are reached.

(17) *Types of blunt impact.* This chapter contrasts the pedestrian headform tests described in chapter 16 with other tests that are, or might be, carried out to test some other manufactured object.

(18) *Effect of speed (and other variables) on HIC (and other variables).* It is assumed that a specific differential equation relates the force at any instant during the impact with instantaneous displacement and instantaneous velocity. Consequences for variables of interest (including HIC, maximum acceleration, and maximum displacement) are then derived mathematically. (For HIC, see sections 16.1 and 18.2.2.)

(19) *Data from impact tests.* It is quite common to test things that may hit a human, or that are intended to protect the human. The analysis of the data is often incomplete. This chapter comments on some published data from transport safety contexts.

Table 1.4. The chapters of Part D. (See section 20.6 for an overview of chapters 20 - 22.)

Part D has three chapters.

(20) *Testing contrasted with real-world variability: Measure-generalise-cost-average.* A test is conducted in particular conditions (e.g., at a specific speed). Real accidents occur in very many different conditions. This chapter is about generalising from particular conditions to a result of broader applicability.

(21) *Testing contrasted with real-world variability: What if several variables affect h?* Chapter 20 considers one quantity (e.g., speed) to be varying in the real world. This chapter extends that to variability in several quantities.

(22) *Testing contrasted with real-world variability: Possible wider application.* Chapters 20 and 21 were chiefly concerned with a pedestrian's head striking a vehicle exterior, or of an occupant's head striking a vehicle interior. But the method proposed might be relevant to many fields of testing.

Table 1.5. The chapters of Part E.

Part E has two chapters.

(23) *Some other specific theoretical issues in road safety: For the future?* This chapter is not concerned with criticising and improving the treatment of the topics considered in this book. Instead, several quite different issues are discussed.

(24) *Concluding comments.* The four sections are:

Is this book all rubbish?

Advantages of theory: Experimental data

Advantages of theory: Road safety practice

Simple messages

## ***1.4 Comments on the approach and contents of this book***

I do not think that the approach in this book will surprise many people in the road safety world. On the contrary, they will see such applications as vehicle assessment that integrates primary and secondary safety (accident avoidance and impact mitigation) as mainstream and in line with what other people are doing and perhaps doing better. See sections 20.5.2 and 20.5.3 for this.

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. Perhaps I mean 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 2.

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). 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 3.4.2 and chapters 4, 14, and 15. (Velocity change is sometimes referred to as  $\Delta V$ .)

*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. In studies with instrumented headforms, 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 chapter 16. 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 16.3.

*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 23.3.

*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 section 23.6, section 23.7, Appendix 7, and Appendix 8.

*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).

*Americanisms and Britishisms.* I doubt if native English speakers will be confused, but I hope this book will also be read by many whose first language is not English. They may not know the following approximate equivalences between American and British English. Automobile = car, Sedan = saloon car, Station wagon = estate car, Hood = bonnet, Tire = tyre, Windshield = windscreen.

## 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  $\times$  and the dot  $.$  are used as symbols for multiplication.

*Power function, and exponent.* When some number  $x$  is multiplied by itself,  $x \times x$ , this is written as  $x^2$ . Similarly,  $x \times x \times x$  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).

- Product of powers of  $x$ :  $x^b \cdot x^c = x^{b+c}$
- Successive raising to power:  $(x^b)^c = x^{b \cdot c}$
- Product of identical powers:  $x^b \cdot y^b = (x \cdot y)^b$

*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:  $\ln(a \cdot x) = \ln(a) + \ln(x)$
- Logarithm of a power:  $\ln(x^a) = a \cdot \ln(x)$

*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. Typical vs. unusual road accidents

I will explain what I mean by typical or ordinary road accidents, as it is these that theory given in this book is most relevant to. It is not necessary to define these categories precisely, but I do need to give some examples.

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.

Very many unusual and extraordinary events can happen in road accidents. The list of examples in section 2.2 is by no means complete.

### 2.1 *Typical (or ordinary) road accidents*

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 angle of impact between the head and the car surface is not likely to be a right angle.)

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 15, especially section 15.4, 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.

## ***2.2 Unusual (or exceptional, or atypical) road accidents***

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 ordinary 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 14.3 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.

### ***2.3 What is the proportion of unusual road accidents?***

In asking this, I am thinking of injury accidents, not damage-only accidents. And I am thinking of the fairly serious ones, not the many minor rear-end impacts (see section 14.3 for some discussion).

The answer to this question is not altogether clear. Typical or ordinary accidents are probably the majority in advanced countries.

- Historically, they were the great majority. But especially for fatal road crashes (which are the ones that cause greatest concern), it is possible that the great advances in road safety that have taken place over the last 50 years have reduced the typical crashes by a greater proportion than the unusual ones.
- Typical or ordinary accidents are still the great majority in developing countries.

It would be desirable to answer the question more exactly.

It has already been noted that quite a number of other road accidents are also sufficiently similar to the typical accidents that much of this book will be relevant to them. Consequently, I believe this book to be relevant to very many road accidents.

### 3. The importance of speed: Empirical data

#### 3.1 *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. 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. There is a little more in section 23.3.)

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 3.4.4.

## **3.2 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 sections 3.4 and 14.2.) 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 that the relationship is specifically a power function with an exponent of about 3.6.

### **3.3 *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.)

### **3.4 *The effect of mass ratio on the probability of death in two-car crashes***

#### **3.4.1 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. In the case of 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. Much of the data below (a) 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.

### 3.4.2 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 14.2.) For a given mass ratio, the ratio of the probabilities of death in the two vehicles is found, 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).

If the proportion of crashes in which the driver is killed is plotted 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. This type of plot is quite popular. But there are two concerns about using it 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.

Instead, suppose the drivers of the two vehicles in collision are compared. Suppose also that the probability of death is assumed to be 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  $[v/(1+R)]^c \cdot N$  to  $[R \cdot v/(1+R)]^c \cdot N$  (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. Consequently, 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.

### 3.4.3 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.

For further results, see Appendix 1.

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.

### 3.4.4 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 3.4.3, 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.

### 3.5 *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.

### ***3.6 How good is the data?***

I suspect that if 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 3.4) 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.

## 4. From travelling to injury: Overview

This chapter and the next, together, will complete the necessary background to the main chapters of this book.

The accidents that are of chief interest are the typical or ordinary ones. As discussed earlier, that includes many car impacts with pedestrians, and many frontal car impacts (with other vehicles or with objects) that may injure the driver and passengers. 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 4.1 and 4.2. Perception of danger and reaction to it is not discussed at this point, but will begin in section 5.2; the initiation or causation of the emergency is largely outside the scope of this book, as was noted in section 1.1.

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".

### 4.1 *Typical 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.
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.

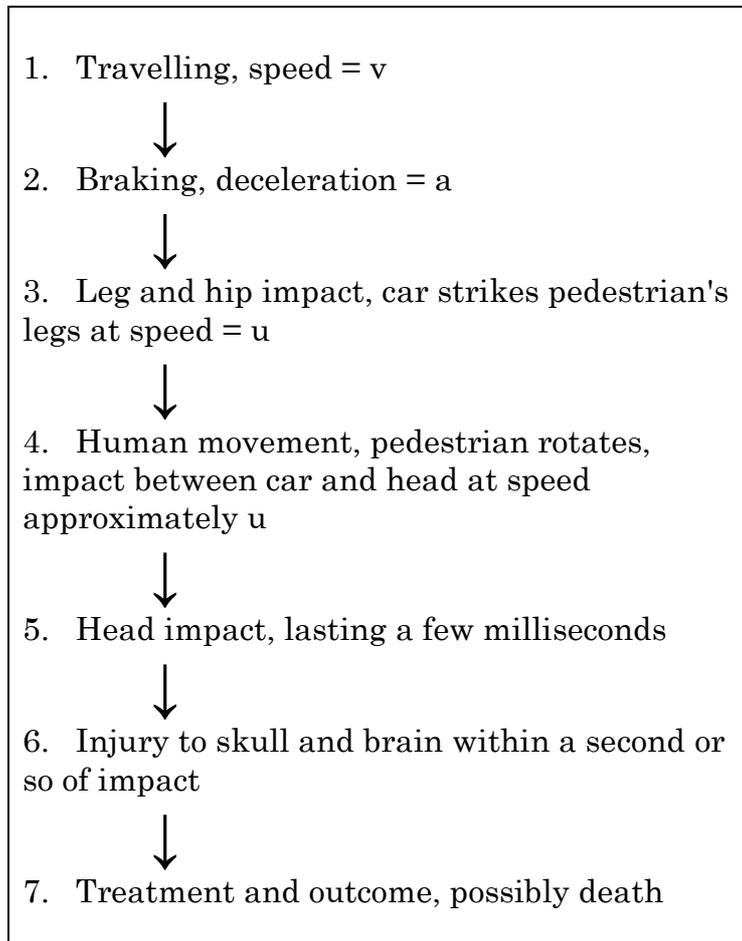


Figure 4.1. Summary of the sequence of events in a typical pedestrian accident. Here and in Figure 4.2, a downward arrow means "is followed by".

## 4.2 *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 14. Simple modelling of the movement of the occupants relative to the vehicle (step 4 above) will be discussed in Chapter 15.

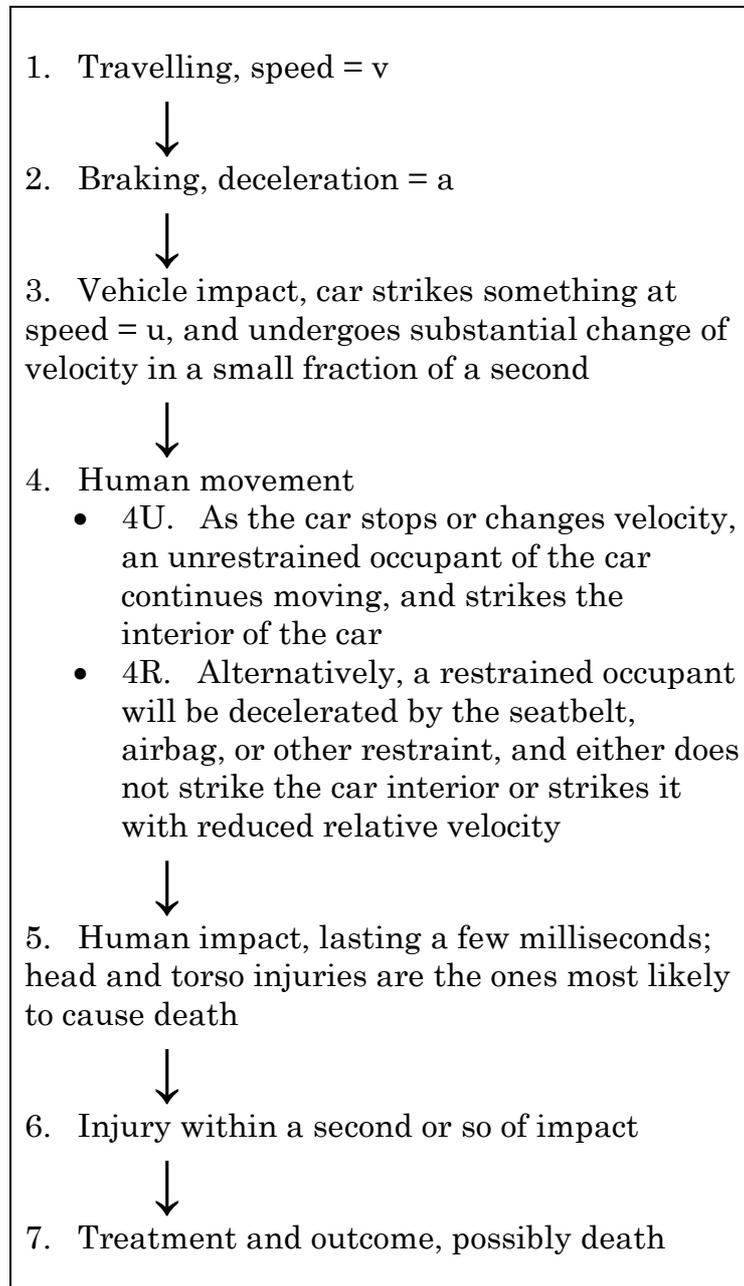


Figure 4.2. Summary of the sequence of events in a typical car occupant accident.

### 4.3 *Comment on injury occurrence*

Injury occurs at step 5 (or perhaps step 4R), 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).

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.

The steps listed in sections 4.1 and 4.2 imply the following reasoning.

- High dangerousness of human impact is chiefly because of high speed of human impact;
- That is chiefly because of high speed of vehicle impact;
- That is in large part because of high speed of vehicle travel.

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? 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.

#### **4.4 *Comment on medical treatment***

Step 7 (sections 4.1 and 4.2) 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.

However, most aspects of this are outside the province of the specialist in road safety.

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.

## 5. Equation for impact speed

### 5.1 *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. If it 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 2 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

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

### 5.2 *What the vehicle might do in an emergency*

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.

In section 8.1, I will consider the rule below, which I will label model [A]. A similar model is in Hutchinson (2015a).

[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, but 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). Chapter 12 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.

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.

There will be similar calculations in chapter 13. Such calculations 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 3), 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 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

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

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.
- Model [A] is clearly expressed.

There is potential danger of loss of control from braking too strongly too 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. Consideration of testing will begin in section 6.2.

### ***5.3 What else the vehicle might do in an emergency***

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. (See especially section 11.3.)
- As will be mentioned in section 12.4, 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 --- that is, at 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. Furthermore, section 11.3 will give some attention to weak braking as a response commanded by AEB, as false positive weak braking might be acceptable to drivers.

### ***5.4 Overview of chapters 2 - 5***

Chapters 2 - 5 have laid the foundations for the main chapters of this book.

Chapter 2 specified what types of road accident are of chief concern. I largely mean typical impacts, rather than typical accidents. In typical impacts, injury is chiefly caused by blunt impact to the human. That may be impact of a pedestrian, or of a car occupant. There was no attempt to give an exact definition or description of what is a typical accident. Quite a long list of unusual types of accident was given: it is unlikely that a theory relevant to them all could be found. Despite the focus on typical accidents, some part of the theory in this book may be relevant to one or other of the people involved, even if the accident is not typical.

Chapter 3 is a briefing about how important speed is for the probability of death. The key empirical finding is that if impact speed is reduced by 1 per cent, the probability of death is reduced by about 3 per cent. Statements like this, of course, are typically made on the basis of "other things being unchanged".

Chapter 4 gave basic information about the sequence of events in typical accidents. There are small differences between pedestrian, unrestrained car occupant, and restrained car occupant impacts.

Normal travelling

Braking (possibly)

First impact (of the vehicle with a pedestrian's legs, an obstacle, or another vehicle)

Human movement (rotation of the pedestrian, or of an occupant within the car)

Human impact (of the pedestrian's head with the car exterior, or of the occupant's head and body with the car interior)

Injury

Treatment and outcome

Most people do not realise that a car bonnet needs to be a cushion so far as a pedestrian is concerned. Most people do not realise that when a vehicle has a normal (perpendicular) impact with an immovable object, an unrestrained occupant hits the car interior with speed approximately equal to the original speed of the vehicle. (Unrestrained refers to someone without a seat belt or air bag.)

Chapter 5 gave an equation for calculating impact speed from travelling speed, strength of deceleration, and distance over which the deceleration acted. It is an elementary equation, one that is often encountered in a mathematics or physics class at school as one of the equations of motion with constant acceleration.

Chapter 5 also suggested a rule or model for how the vehicle or its driver might behave when it encounters an obstacle directly ahead. This model might describe the behaviour of a vehicle with Autonomous Emergency Braking (AEB), or the behaviour of one with a human driver.

- This model uses three characteristics of the vehicle or driver: a range, a reaction time, and a strength of deceleration.
- What happens depends on those characteristics and on two features of the situation: the travelling speed of the vehicle and the distance of the obstacle.
- The most important aspect of what happens is whether the vehicle hits the obstacle, and, if so, at what speed.

It is a very simple model. Some complexities will be discussed later in this book. As the effect of impact speed on probability of death is strong (see chapter 3), even a simple model that describes the last second or so before impact is well worthwhile.

## Part B. Emergencies: Detection and reaction

Part B has the following chapters.

6. Autonomous emergency braking.
7. Interpretation of AEB test data from a sudden challenge.
8. A model for AEB operation.
9. Interpretation of AEB test data: Testing without access to the vehicle's internal communications, and using a continuously-viewed obstacle.
10. Data from AEB testing by Hulshof et al. (2013).
11. Discussion of AEB testing and the data.
12. How to construct your own model.
13. The effect of travelling speed on impact speed: Quantitative demonstration.

Chapter 8 is the most important of Part B, and then chapter 9 adapts the model and equation to a continuously-viewed obstacle.

- Chapters 6 and 7 are preparation.
- Chapter 10 examines some data from testing.
- Chapters 11 - 13 wrap up the topic.

There are overview sections, each covering two or three chapters, at the ends of chapters 8, 10, and 13.

The discussion here of testing of AEB systems is fairly abstract. The difficulties of testing are ignored: this book is not about the practicalities. But I should acknowledge that many people have put much effort into developing methods of testing, and they continue to do so. I will suggest certain tests that would be useful for comparison with a model such as [A] (which was given in section 5.2), but it is possible they might not be practicable.

## **6. Autonomous emergency braking**

### **6.1 Introduction**

At the present time, there are fully autonomous vehicles operating in ordinary traffic on ordinary roads in some jurisdictions, and many other vehicles that have one or other form of autonomous braking. Fully and partly autonomous vehicles have control systems, which in turn rely on sensing systems.

Exactly how such systems work appears not to be in the public domain, though many generalities are known. Numerous publications give the impression that for some years past, the operation of autonomous braking systems has been more sophisticated than the description at [A] (section 5.2). In that sense, then, the model at [A] might be considered pessimistic. And if a system operating according to [A] is likely to improve safety considerably, a realistic system may be even more effective. Some researchers are sufficiently optimistic about the analysis of potential conflicts by AEB systems that they have considered autonomous braking earlier in the sequence of events, at about the time a driver feels discomfort about (for example) the proximity of a pedestrian (Lubbe and Davidsson, 2015).

It is not necessary to prevent many impacts. A reduction of impact speed of even 1 km/h would be worthwhile, as the percentage reduction in fatalities is likely to be a multiple of the percentage reduction in impact speed (see chapter 3). Eckert et al. (2013, p. 2) also emphasise mitigation rather than avoidance of impacts.

In the medium term, AEB systems may not be fully effective, in that high speed impacts will largely be reduced in speed rather than prevented. Even presuming that technical problems have been overcome, there is inherent difficulty at a high speed, and therefore a long time and a long distance, of making an accurate prediction about what another road user will do. Nevertheless, this mitigation of impacts will be very worthwhile (assuming percentage reduction in fatalities is a multiple of the percentage reduction in impact speed).

### **6.2 Methods of testing**

#### **6.2.1 Several strategies of testing**

A number of methods of testing autonomous vehicles have been developed. For example, a vehicle might be driven towards an obstacle,

and it is observed whether or not the vehicle autonomously brakes to a halt before striking the obstacle.

It is desirable to get as much information as possible from a test or a series of tests. For example, if a vehicle successfully stops from a speed of 20 km/h, can it be said whether it would also stop from a speed of 30 km/h, or 60 km/h? If only the simplest information has been collected --- success vs. failure --- success at an easy task has no implications for performance on a difficult task. But if appropriate data has been collected from the test, some inferences might be possible.

To understand test results, some theory is needed of how the vehicle behaves in an emergency.

- Model [A] above (section 5.2) is an example of such a theory.
- Equations in section 5.2 predict impact speed from travelling speed  $v$  and some other quantities that include a reaction time  $t$  and a range  $d$ .
- One can therefore imagine conducting a small number of tests at known speeds, and using the observed impact speeds to estimate what  $t$  and  $d$  are for the vehicle being tested.
- Then those estimated quantities can be used to predict impact speed at other travelling speeds.

To make such an idea usable, the method of testing needs to be specified. Several types of testing may be envisaged. Four examples are as follows.

- The car, which is equipped with AEB, is driven at a known speed towards a stationary obstacle. The obstacle is soft, so that it is unlikely that the car will be damaged if impact occurs. What is of interest is whether the car stops before impact (or, if impact takes place, what is the speed of impact).
- The obstacle may instead be moving transversely, representing a pedestrian coming from the footpath on to the road.
- Methods in which the car's internal communications are accessed would make it possible to identify the moment that the AEB system commands emergency braking.
- Methods using a static vehicle, rather than a moving vehicle on a test track.

### **6.2.2 Testing other aspects of operation**

There are also many other types of testing with different aims. They include checking that the AEB system works in all environmental conditions (e.g., lighting and weather conditions), that it operates in a way that is acceptable to human drivers, that the rate of false positives (i.e., emergency braking when that is not needed) is acceptably low, and so on.

The false positive problem may be a very difficult one. A possible way of overcoming it may be for AEB systems to command emergency braking only when the vehicle is very close to the possible obstacle. Eckert et al. (2013, p. 6) are also concerned about false positives, and note that attempting to predict a pedestrian's movements risks greatly increasing the number of false positives. However, Grover et al. (2015) say that "It is understood that the extremely good performance of the Lexus is enabled by the use of a path prediction algorithm that enables the brakes to be applied a short time before the pedestrian enters the vehicle path". This refers to the Lexus LS460 in pedestrian AEB tests of the type to be described in section 6.2.4 below (the highest speed tested was 60 km/h). It is a very interesting comment --- I would have said that inability to predict a pedestrian's movement places a permanent limit on AEB effectiveness.

### **6.2.3 Euro NCAP, with a mock vehicle as the target**

For the Euro NCAP (New Car Assessment Programme) test protocol for AEB systems, see Euro NCAP (2013a). This protocol has the following general characteristics.

- The vehicle equipped with AEB is on a test track. A physical target resembles a vehicle.
- The test reflects the performance of the whole vehicle, including the AEB system, brakes, and tyres.
- The target does not appear suddenly (it is either stationary or moving in the same direction as the vehicle being tested).
- The vehicle under test is driven towards the target at a steady speed. This is repeated at increasing speeds until the vehicle fails to stop before the target.

Results of Euro NCAP tests using a stationary target were announced in Euro NCAP (2013b). The maximum speed from which the vehicles stopped before reaching the target was typically 27 km/h, and the maximum speed at which there was impact mitigation was typically 32 km/h (those are the medians of 6 vehicles tested).

### **6.2.4 Euro NCAP, with a mock pedestrian as the target**

The tests in Euro NCAP (2013b) did not mimic pedestrian impacts. More recent tests do --- the strategy is for a physical target resembling a pedestrian to move into the vehicle's path from the side. There are four variants of the test, three representing adult pedestrians and one representing a child pedestrian appearing from behind parked vehicles.

The target moves into the vehicle's path at a greater distance in front of the vehicle when the vehicle is travelling fast than when it is travelling slowly. This is a consequence of it being specified that the target needs to

reach a certain point across the width of the car at the moment the car would reach it if there were no braking. The vehicle is therefore at a distance  $r.b$  when the target moves into its path, where  $r$  is the ratio of the vehicle speed to the pedestrian speed and  $b$  is the distance the target has to move to. (In one of the variants of the test, for example, the distance  $b$  is a quarter the width of the vehicle, about 0.45 m, and the target moves at 5 km/h.)

A vehicle speed of 60 km/h and a distance of 5.4 m is not necessarily a more difficult task than 20 km/h and 1.8 m. For example, the slower speed is a more difficult task if the vehicle's sensors are only sensitive to objects within a narrow angle from its centreline, and do not detect objects that are at a wider angle (Seiniger et al., 2015, p. 5 and p. 7). As noted in section 27.5, some failures of AEB at low speeds were observed in the results of Seiniger and Gail (2015).

For this testing method, see Schram et al. (2015), and there is some further information in Pla et al. (2014), Grover et al. (2015), and Seiniger et al. (2015). For discussion of results reported by Seiniger and Gail (2015), see section 11.2 and Appendix 3.

### **6.2.5 Intoxicated pedestrians**

A substantial proportion of pedestrians killed and injured are very intoxicated. That finding dates back at least to a study by Heise (1934) in Uniontown, Pennsylvania; see, for example, Hutchinson, Kloeden, and Lindsay (2011). Some of these intoxicated pedestrians behave similarly to other pedestrians in the second or two before the accident, but some of them do not. Prediction of behaviour one or two seconds in the future is likely to be even more difficult for intoxicated pedestrians than for sober pedestrians.

Further, some AEB systems do not operate, or do not operate well, in darkness (and many of the intoxicated pedestrian accidents occur in darkness).

Thus it may be that AEB will not, in the medium term, be very effective for this important class of accidents.

## **6.3 AEB at the 23rd ESV Conference**

### **6.3.1 Defining and inferring properties of the AEB system**

There were several papers relevant to AEB at the 23rd ESV (Enhanced Safety of Vehicles) Conference in 2013, and some showed interest in defining and inferring properties of the AEB system.

- Wisch et al. (2013, p. 12) refer to the time needed for detection (of a pedestrian) as a relevant target and the time needed to increase braking from zero to maximum. (They do not, however, define the durations of these times, or when they begin and end.)
- At p. 10 of Hulshof et al. (2013), there are brief comments attempting to infer from the test results how the systems work. The data will be discussed in chapter 10 below.
- Eckert et al. (2013, pp. 5, 7) give a simple equation for stopping distance, show that braking system performance is important for impact speed, and mention the importance of "prediction horizon" (which is a time, about 1 sec, but is not explained precisely) for both reduction in impact speed and false positives.
- Chauvel et al. (2013, p. 4) give a simple equation for impact speed, and they consider that emergency braking would be triggered 0.6 sec before impact.
- Hayashi et al. (2013) give several diagrams that illustrate difficulties that an AEB system needs to overcome.
- Anderson et al. (2013) propose some rules according to which an AEB system might operate. These are of the following form. (a) If there is an obstacle present within the system's detection area, computation time starts to elapse. (During this, the obstacle is observed and a prediction is calculated of its future movement relative to the vehicle with AEB.) (b) After a fixed duration of computation time, a prediction is made of whether a collision will occur (within a certain time). (c) If a collision is predicted to occur, braking with deceleration begins immediately.

### **6.3.2 Details of testing methods**

Descriptions are given of testing methods, including some details. For example, Wisch et al. (2013) suggest some practical test scenarios. Their distinction between obstructed and unobstructed scenarios is similar to the concern here with challenge distance, as an obstructed scenario implies that the challenge may occur very close to the vehicle, whereas an unobstructed scenario is likely to correspond to a challenge at a greater distance.

Other relevant papers include Ando and Tanaka (2013), Aparicio et al. (2013), Bours et al. (2013), Eckert et al. (2013), Hamacher et al. (2013),

Hulshof et al. (2013), LeBlanc et al. (2013), Lemmen et al. (2013), Sandner (2013), Schram et al. (2013), Yi et al. (2013), Yuasa et al. (2013), and Zecha et al. (2013).

### 6.3.3 Effectiveness, or otherwise

AEB systems were at that time at quite an early stage.

- Tests of two AEB systems by Ando and Tanaka (2013), using a dummy pedestrian, found that one was reliable only below about 30 km/h and the other was reliable only below about 10 km/h.
- The maximum speed from which a vehicle can be stopped before reaching an obstacle is typically 25 km/h; that is the median of 11 systems tested by Hulshof et al. (2013), with the minimum being 20 km/h and the maximum 50 km/h. The vehicle under test was driven directly towards the obstacle, which was a dummy car.
- Referring to tests at up to 40 km/h with a dummy pedestrian, the results in Figure 19 of Lemmen et al. (2013) show that in some cases the vehicle stopped and in others it did not; Lemmen et al. note that in some cases good performance was achieved by braking early, and thus false positives are a possibility.

### 6.3.4 Further points

Most methods test the whole vehicle, and thus are sensitive to the braking system and tyres as well as the AEB system.

- The importance of the braking system is emphasised by Eckert et al. (p. 7), and it may be calculated from their Figure 11 that an existing premium brake control system improves on a standard system by about 0.11 sec, and that an advanced braking system improves by a further 0.08 sec.
- Hayashi et al. (2013) also emphasise the importance of the braking system.
- A later paper (Jeppsson et al., 2018) attempted to estimate the benefits from AEB and from AEB plus a vacuum emergency brake. The condition for activation of AEB was similar to, or the same as, that in Rosén (2013), which will be discussed in sections 8.1.4 and 9.1; the improvement in deceleration from a vacuum emergency brake was considered to be between 30 per cent and 80 per cent. Then from comparison with what happened in real accidents, it was estimated that AEB would reduce deaths by 72 per cent, and that a further 13 per cent reduction would be achieved by a vacuum emergency brake that improved deceleration by 55 per cent.

Most methods use measurements available outside the vehicle, they do not plug into the vehicle's electronics.

With these methods, it is practicable, time-wise, to test at several speeds within a period of a few hours.

Eckert et al. (p. 7) and Chauvel et al. (2013, Table 1) consider that deceleration as high as 10 m/sec/sec may be achievable in emergency braking, and this was indeed the case for some vehicles in the tests reported by Hulshof et al. (see chapter 10 below).

## **6.4 AEB at the 24th ESV Conference**

### **6.4.1 Tests mimicking real fatal pedestrian accidents**

Vertal et al. (2015) selected 18 fatal pedestrian accidents from a large database. They gained some extra knowledge about these by simulation. They then conducted tests with a Volvo V40 (model year 2014) equipped with AEB.

The average impact speed for the sample of 18 cases was 36 km/h. That seems rather low to me for fatal cases. In 10 of the 18 cases, the pedestrian was aged 70 or more. That seems a rather elderly sample to me. (There are many elderly people among those killed, and this group should not be neglected, but their accidents may be unrepresentative in respect of impact speed, as a proportion die from impacts that a younger person would probably survive.)

As far as I can see, Vertal et al. do not report travelling speed before the emergency. They do report estimated impact speed in each real accident. I think it likely that these speeds were used as travelling speeds in the tests. It may have been that they were also the travelling speeds in the real accidents, and that the sample was one of cases in which there was no braking before impact. For the case presented in detail, Vertal et al. state that the driver did not react.

Vertal et al. reported the results of checks of whether the AEB system works in some difficult situations. Vertal et al. do not define what they mean by brake lag time, but they report it as about 0.5 sec, rather larger than with a driver braking (0.2 sec).

In 4 of the 18 cases, the vehicle was cornering, in 1 case the vehicle was overtaking, and in 1 case the pedestrian was lying on the road. For the remaining 12 cases, vehicle speed was between 19 km/h and 50 km/h. The speed reduction achieved by the AEB system averaged 26 per cent. The percentage reduction tended to increase with vehicle speed (0 per cent for 0-29 km/h, 26 per cent for 30-39 km/h, and 45 per cent for 40-50 km/h).

### 6.4.2 Simulations mimicking real pedestrian accidents

Páez et al. (2015) had a sample of 50 pedestrian accidents from Madrid that were subject to in-depth investigation and reconstruction. They simulated what would have happened if the vehicles had been equipped with DaimlerChrysler's PROTECTOR system (see section 8.1.4 for this). The speed reduction averaged 59 per cent (data in Figure 4 of Páez et al., 2015).

### 6.4.3 Real-world accidents

The paper by Doyle et al. (2015) is valuable for at least three reasons: the descriptions of the City Safety (Continental, Volvo) and Front Assist (Bosch, Volkswagen) systems, the literature review of accident studies, and their own accident study.

The empirical work used car insurance claims data, comparing two cars with AEB with similar vehicles. The two cars were Volvo XC60, equipped with City Safety, and VW Golf 7, with Front Assist. In both cases, claims losses (e.g., Third Party Injury) were lower for the vehicle with AEB.

- It seems likely that many of the claims were against the striking vehicle in rear-end crashes.
- It might be suggested that in such crashes, the third party might press their claim less strongly, or the insurer of the striking vehicle might resist the claim more firmly, if the striking vehicle is equipped with AEB. I have no reason to think this, but it would be desirable to find relevant evidence.

### 6.4.4 Other topics

Other papers are mentioned elsewhere in this book. These include information about Euro NCAP test methods (sections 6.2.2, 6.2.4, 11.2, and 16.2), weak braking as an autonomous action (section 11.3), results obtained in AEB tests (section 11.2 and Appendix 3), integrated assessment of primary and secondary safety (section 20.5.2), and pop-up bonnets (section 16.2). Papers by Ferenczi et al. (2015) and Wimmer et al. (2015) are rather similar in general approach to this book, and these are discussed in section 20.5.3.

## 7. Interpretation of AEB test data from a sudden challenge

How effective is an AEB system in a particular vehicle likely to be? The definition and measurement of this is likely to be much easier if it is possible to unambiguously measure the time elapsing from a challenge by an obstacle to a command for emergency braking.

- The need to define the start of this period of time suggests the use of a sudden challenge, rather than a continuously-viewed obstacle.
- The need to define the end of this period suggests that access to the vehicle's internal communications (e.g., the communication between the AEB system and the braking system) will be needed.

### 7.1 *AEB when very close to, or further from, an obstacle*

Consider a vehicle that is travelling at 50 km/h, i.e., 14 m/sec.

- Suppose that an obstacle, perhaps a pedestrian, suddenly appears in front of the vehicle at a distance of, say, 9 m.
- At 14 m/sec, 9 m corresponds to about 0.64 sec.
- The obstacle cannot be avoided. But vehicles can brake at (say) 8 m/sec/sec.
- A reduction in reaction time of 0.1 sec would imply a reduction in impact speed of 0.8 m/sec. (Of course, this assumes reaction is sufficiently quick that braking begins, but not sufficiently quick that impact is avoided.)
- That is about 6 per cent of the travelling speed, and a rather greater percentage of impact speed.
- It is widely thought that percentage reduction in fatalities is a multiple (perhaps three times) of the percentage reduction in impact speed. (See chapter 3.)
- A rough estimate of the reduction in fatalities in this type of crash is thus 18 per cent for each 0.1 sec improvement in reaction time.
- Every step here is only approximate, and certainly the final 18 per cent could be appreciably in error. Nevertheless, this calculation is sufficient to qualitatively demonstrate that small reductions in reaction time will be very worthwhile.
- For more of this type of calculation, see chapter 13.

Consideration of the operation of AEB at longer distances (25 m, say) is much more difficult. For a car travelling at 50 km/h, 25 m is equivalent to 1.8 sec. A pedestrian walking at 1.4 m/sec will move 2.5 m in that time, which is potentially from one side of the car to the other. This makes it plain that the task for the AEB system is very difficult.

## 7.2 *Sudden challenge*

Reaction time is likely to be important, and therefore a test of AEB should include estimation of this. Concepts relevant to obstacles further away in space and time are less clear.

The straightforward way of estimating reaction time is with a sudden challenge. (Nevertheless, information could be gained from tests with a continuously-viewed obstacle. To use that information to infer reaction time will require a model or theory about AEB, as in section 9.6 below.)

The test envisaged in this present chapter is of the following type.

- The test should measure the reaction of the AEB system (or the vehicle) to an obstacle clearly in its path, that is, a "challenge" to the system. Closely-related aspects of the AEB system may also need to be tested --- for example, its reaction or non-reaction to an obstacle close to the vehicle's path at the side, to a moving obstacle, and to obstacles of various sizes and with various surfaces. It seems likely such tests could be modifications of what will be proposed.
- Emergency braking is the appropriate response to the challenge. At some point the AEB system commands this, and it is assumed that the moment of doing so can be identified. This might be by plugging into the AEB system or the braking system somehow; discrepancies reported by Beuse et al. (2013) suggest that the exact method may be important.

Methods that do not rely on plugging into the vehicle's electronics, and refer to the performance of the whole vehicle (including the AEB system, the brakes, and the tyres) are also likely to be useful: see chapter 9.

## 7.3 *Testing*

Adopting a direct approach to measuring reaction time, an AEB system (or some aspects of it) might be tested as follows.

- A vehicle is driven at speed  $v$ .
- It is suddenly (instantaneously) challenged by an obstacle a distance  $x$  ahead of it. (In terms of time, that is a time  $x/v$  ahead of it.) For example, something pops out of the ground, or is quickly dragged or projected into the vehicle's path.
- The time from that challenge until the AEB system commands emergency braking is measured.
- The data consists of observations of that time, associated with  $x$  (and with  $v$  also being known).
- Another measure of performance is distance available for braking.

Either reaction time or distance available for braking would refer to the AEB system --- but as regards injury, performance will need to include the speed reduction achieved by braking, also.

Such a test might mimic any type of obstacle in the vehicle's path; vulnerable road users such as pedestrians are particularly important as their injuries tend to be more severe than those of vehicle occupants. See section 6.2.4. In the case of many present methods, there is an obstacle or target towards which the vehicle is driven, but it is continuously present rather than suddenly appearing from nowhere (see section 6.2.3). And most existing methods use measurements outside the vehicle, rather than needing to plug into the AEB system. Chapter 9 will adapt the proposed method to these methods.

## **7.4 Discussion**

Model [A] includes no provision for an obstacle outside the path of the vehicle to be tracked by the AEB system, with the AEB system reacting very quickly if the obstacle comes into the path of the vehicle. Consequently, the method of testing does not try to measure any benefit there might be from having the obstacle in view for a longer time.

It is worth considering the possible benefit of weak braking. The importance of this is that false positive braking might be acceptable to the driver if the deceleration were only 1 m/sec/sec or 2 m/sec/sec. If it lasted 0.5 sec, speed reduction would be 1.8 km/h or 3.6 km/h (0.5 m/sec or 1.0 m/sec). By the same reasoning as in section 6.1, this itself should lead to a worthwhile reduction in fatalities, even if there were no further speed reduction from emergency braking. Discussion of this will be continued in section 11.3.

At present, there is much unknown about how AEB systems will operate in practice. My current attitude is optimistic pessimism: pessimism about impact prevention, but (on the basis of examples such as that in section 5.2) optimism about impact mitigation. A reduction of impact speed of even 1 km/h would be worthwhile.

## 8. A model for AEB operation

It is assumed that at a particular moment there is a definite "challenge" to the vehicle, that the distance between the challenge and the vehicle is known, and that the time from the moment of challenge to a command for emergency braking can be measured.

The following approach will be taken.

- Concepts are hypothesised that are characteristics of the AEB system under test --- that is, their numerical values do not depend on test conditions such as challenge distance or vehicle speed.
- A good measure of AEB system performance (considered in isolation) in given conditions is the distance available for braking at the moment when the AEB system issues a command for emergency braking.
- It seems sensible to do a number of tests to examine how this distance depends on challenge distance and vehicle speed.
- The results can be used to infer the numerical values of the characteristics of the AEB system.
- These can be used, along with assumptions about real-world accident events, to estimate the average in real traffic conditions of distance available for braking.

### 8.1 *Model [A]*

#### 8.1.1 Introduction

A description of the operation of an AEB system will be proposed below. The obstacle that will be referred to might be anything (e.g., a stationary vehicle), but pedestrians are particularly important.

This is not intended to be a complete description of a real system. Rather, it is intended to represent what is likely to be important in saving lives and serious injuries, and to be fit for its chief purpose of predicting what will happen in other conditions from what is found to happen in test conditions. What is important for prevention and mitigation of (the much more frequent) low-speed rear-end crashes may be different. Some variations on this description will be noted, especially in section 8.5 and chapter 12.

I regard the general style of the analysis --- that is, the type of experimentation envisaged, the simplicity of the rule assumed to govern AEB operation, and the variables used --- as more important than the details. Section 6.3.1 noted that there was some interest in such analysis at the 23rd ESV Conference, but what was done was elementary.

### 8.1.2 Description

The following model of AEB operation was proposed earlier (section 5.2) and termed model [A]. It is intended to be relevant to a vehicle that is not following another vehicle.

[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  $t$ .

Thus the idea here is that there is a range  $d$  and a reaction time  $t$  that need to be measured by a test.

- The "range" means that in commanding emergency braking the system is only concerned with obstacles within a distance  $d$  in front of the vehicle.
- "Reaction time" means that provided the obstacle is within a distance  $d$ , a time  $t$  elapses before the system commands emergency braking.

Large  $d$  and small  $t$  are desirable, always presuming that false positives are very rare.

Deceleration  $a$  is, for the moment, not relevant. Focus is on the moment when emergency braking is commanded, and deceleration comes later.

### 8.1.3 Comments

Model [A] may be realistic or unrealistic, sufficiently accurate or too inaccurate. At least it is a starting point. Even someone who knows how AEB really works might simplify it to model [A]. Chapter 12 will suggest some building blocks from which better models might be constructed.

Some people may agree with me that a simple model is useful, but will claim that the range ought to be a time rather than a distance. The concept of "time to collision" (TTC) has been used by a number of workers, and they may want a value of TTC to replace  $d$ . (TTC is calculated from the ratio of distance to speed, assuming no acceleration.) I think it likely that belief in the usefulness of TTC arises because many a thing is an obstacle to a vehicle at one moment or another, and then ceases being an obstacle: it moves out of the vehicle's path, or the vehicle's driver steers or brakes to avoid it. There is high danger when there is insufficient time for it to move away, or for the driver to react.

- Suppose there is an obstacle directly ahead at a distance  $x$ , and the vehicle will avoid it by moving (by steering) a distance  $x_{lat}$  laterally. (This is determined by the lateral position of the obstacle and the widths of it and the vehicle.) The time available is TTC, calculated

in the usual way as  $x/v$ . If the vehicle moves with lateral acceleration  $a_{lat}$ , the lateral distance moved in time TTC is  $\frac{1}{2} \cdot a_{lat} \cdot (TTC)^2$ .

- It might be assumed that  $a_{lat}$  is a constant (for a vehicle with given capability and a driver with given preference for lateral acceleration). Thus for a given distance  $x_{lat}$  required to avoid the obstacle, the condition is to the effect that TTC is sufficiently big. Specifically, TTC must exceed  $\sqrt{(2 \cdot x_{lat} / a_{lat})}$ .
- Suppose that  $x_{lat}$  is 1.8 m (approximately the width of a car), and that  $a_{lat}$  is 7 m/sec/sec (Brännström et al., 2010, p. 665, give this value). Then emergency steering needs to occur if TTC falls to 0.72 sec. Brännström et al. show TTC of about this in their Figure 13.
- It is of interest that if this model of emergency steering is realistic, emergency steering may be successful at some high speeds at which emergency braking is not successful in avoiding impact: see, for example, Malaterre et al. (1988).

In contrast, I very much want AEB to operate effectively at quite high speeds, and I think processing time will be crucial. My opinion at present is that a distance is more plausible if one thinks that processing power limits the performance of an AEB system. For further discussion, see section 8.5.1.

#### 8.1.4 Comparison of model [A] with some alternatives

The model and equations are quite similar to those in Rosén (2013). That paper, however, does not have the same emphasis on results of testing leading to inference of model parameters, in turn leading to prediction of performance in other conditions. Rosén's model is also considerably more complex, including an angle describing the field of view of the sensor, a width referring to the field of view of the sensor, and a ramp-up time for the brakes. The case against such complexity is that it implies more testing in order to estimate the extra parameters. Rosén's model uses a time instead of a distance  $d$ , as will be discussed in section 9.1. The same is true of the models of Seiniger et al. (2013) and Lubbe and Kullgren (2015).

Minamoto et al. (2010) considered a vehicle with a collision mitigation brake (CMB) approaching a stationary obstacle. They appear to use the following rule for operation of the CMB.

CMB starts operation when the vehicle is at a certain time from the obstacle (the time being the ratio of distance to speed). Operation consists of a demanded deceleration. Before the demanded deceleration, there is a ramp-up of 1.2 g/sec.

Some information is given about the sensor: it has a horizontal view angle that is plus or minus 8 degrees, and a range (150 m). Minamoto et al. consider critical times of 0.6, 1.0, and 1.4 sec, and demanded decelerations

of 0.5 g and 1.0 g. (The ramp-up is sufficiently gradual that it takes 0.83 sec for demanded deceleration of 1.0 g to be reached.) Actual deceleration may fall short of the demanded deceleration, either because the road surface may not be good enough to provide high deceleration (Minamoto et al. consider friction coefficients of 0.3, 0.6, and 1.0), or as a consequence of the vehicle handling model used (which has details of the four tyres). I have two comments about the rule for operation: the range of 150 m is far greater than what I have in mind, and the slow ramp-up appears to take the place of a reaction time.

Páez et al. (2015) describe how DaimlerChrysler's PROTECTOR system operates. I do not fully understand the description, but it seems to be approximately as follows.

There is a rectangular danger zone ahead of the vehicle. Longitudinally, it extends from 5 m to  $D_{\text{risk}}$  ahead of the vehicle ( $D_{\text{risk}} < 25$  m). Transversely, it extends 1.5 m either side of the centreline of the vehicle (or is bounded by the edge of the road if that is nearer). If there is a clear sight line to the pedestrian and the pedestrian is within the danger zone, deceleration of strength  $a_{\text{PROT}}$  begins after a time  $t_{\text{BAS}}$ .

If my understanding is correct, this is very similar to model [A]. Páez et al. (2016) give some information about five AEB systems, including maximum brake activation distance, detection angle, and range.

## 8.2 *Comments on d and t*

In a test, the meanings of  $d$  and  $t$  are seen in their effects. Firstly, if challenge distance  $x$  is less than the distance  $d$ , the observed time from stimulus to reaction is the reaction time  $t$  (constant). Secondly, if  $x$  exceeds  $d$ , the observed time from stimulus to reaction is the time taken to move to within distance  $d$  of the obstacle (that is, time  $(x - d)/v$ ) plus the reaction time  $t$ . Overall, then,

observed time from stimulus to reaction =  $t + \max\{0, (x - d)/v\}$

The foregoing equation permits  $d$  and  $t$  to be estimated. Although it is hoped that range and reaction time are suitable names,  $d$  and  $t$  are not defined by these names but implicitly by the equation. They may be used to calculate the distance available for braking,  $y$ :

$$y = \min\{x, d\} - v.t$$

In turn, this distance can be used to calculate impact speed.

The operational characteristics  $d$  and  $t$  may in part be consequences of processing limitations of the "sensors" and "brain" of the AEB system, and in part be settings chosen to ensure that false positives are rare.

It is not the case, with this model, that there is distance to spare and the system can delay until reaction becomes definitely necessary. Concern with deaths and serious injuries implies fairly high speeds are relevant, and consequently the system's task is a difficult one. At 60 km/h (about 17 m/sec), the braking distance required to stop is about 17 m if deceleration is 8 m/sec/sec, and consequently immediate emergency braking is likely to be the appropriate response to a challenge at 5 m or 10 m. In contrast, at 20 km/h (about 6 m/sec), the braking distance required to stop is about 2 m, and immediate emergency braking might not be the reaction to a challenge at 5 m or 10 m. (For weak braking as a reaction, see especially sections 7.4 and 11.3.) Furthermore, sometimes when the situation appears dangerous, the driver is about to steer past the obstacle.

### 8.3 *Tests needed*

Two tests are needed to estimate or measure  $d$  and  $t$ .

- One must be at such a close distance that the AEB system will not wait until getting closer but will operate as soon as possible. This test gives  $t$ . (For practical reasons, the distance may need to exceed some minimum.)
- The other must be at sufficient distance that there will be some time before the car comes within range and reaction time starts to elapse. Suppose that challenge distance is  $x$  and observed time is  $t_{\text{obs}}$ . Then  $t_{\text{obs}} - t$  is the wait, the distance travelled in that time is  $v \cdot (t_{\text{obs}} - t)$ , and thus the range  $d$  is calculated as  $x - v \cdot (t_{\text{obs}} - t)$ .

At present, there is not wide experience with a variety of AEB systems. Thus it would be highly desirable to carry out more tests at various different challenge distances  $x$ , even though only two tests are actually needed to enable  $t$  and  $d$  to be estimated. The equation in section 8.2 for observed time is a model for the behaviour of AEB, and a plot of  $t_{\text{obs}}$  versus  $x$  would show whether or not the model is successful in predicting  $t_{\text{obs}}$  (with  $v$  known and  $d$  and  $t$  to be determined). The relationship has two parts.

- For small challenge distance  $x$ , the observed time does not depend on  $x$ , and is  $t$ .
- For a challenge distance that exceeds  $d$ , the observed time increases linearly with  $x$ , and is  $t + (x - d)/v$ .

If the description of AEB operation is wrong, then presumably the pattern of the data will not be as described here. Testing is difficult, and consequently real data is nearly always messy, and neat straight lines of slopes 0 and  $1/v$  (that intersect at  $x = d$ ) may not be at all likely in practice. But if data is not obviously suggestive of that pattern, it may at least be compatible with it.

If range and reaction time really are appropriate names, then the choice of  $v$  (e.g., 60 km/h) does not matter --- but this should be checked by conducting tests at different speeds. According to the model,  $t$  and  $d$  would remain the same, what would change would be the slope of the relationship when challenge distance exceeds  $d$ .

#### ***8.4 Effectiveness of an AEB system: Distance available for braking, and impact speed***

Distance available for braking is viewed here as being the appropriate way to describe how successful the AEB system is (given the distance of the challenge and the speed of the vehicle, of course). That means that for challenges at distances greater than  $d$ ,  $d - v.t$  is the important quantity, and for challenges at distances less than  $d$ ,  $t$  is the important quantity. Thus tests at both a short distance and a long distance are desirable.

Impact speed has a closer relationship to injury severity than does distance available for braking. If emphasis is on the performance of the AEB system, it is likely that distance available will be preferred; if emphasis is on the performance of the vehicle (including of its braking system and tyres), it is likely that impact speed will be preferred. In the present conceptualisation, the AEB system detects (or begins to covertly react) at distance  $x$  or  $d$  (whichever is the smaller), and reaction consumes a distance  $v.t$ . Thus the distance available is  $\min\{x, d\} - v.t$ , and the square of impact speed is  $v^2 - 2.a.(\min\{x, d\} - v.t)$ . This is subject to some conditions, that distance is sufficient for reaction time to expire and distance is not sufficient for the vehicle to stop. Making allowance for these, the expression for the square of impact speed is

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

This equation was given earlier (section 5.2).

Delay in brake operation has been assumed to be zero, and  $a$  is assumed to be known.

The proportions of challenges at different distances are obviously important for the real-world average performance of AEB. Suppose that empirical data on challenge distances  $x$  and speeds  $v$  were available. (Such a dataset was used by Hamdane et al., 2015.) By doing lots of calculations using the equations given, such data could be used to generate a distribution of distance  $y$  (section 8.2) and a distribution of impact speed  $u$ . These distributions will depend on  $d$  and  $t$ , of course. Even before estimating these, it would be possible to determine the effect of different assumptions about  $d$  and  $t$  on the distributions of  $y$  and  $u$ .

## 8.5 *Variations on the description of AEB operation*

It is certainly not claimed that model [A] is the last word on the matter. Rather, it is intended to be an appropriate balance between convenient simplicity and more realistic complication.

Four types of variation on the above description will be noted below. Models used by Minamoto et al. (2010), Rosén (2013), and Páez et al. (2015) have already been mentioned in section 8.1.4. For further possibilities, see chapter 12.

### 8.5.1 **A time $t^*$ instead of a distance $d$**

A time  $t^*$  might be proposed instead of a distance  $d$ , and in that case,  $v \cdot t^*$  would replace  $d$  in the equations.

The following reasoning suggests a constant  $d$  is a better assumption than a constant  $t^*$ . An AEB system processes information. It might examine, for example, whether an obstacle is evident in the image up to a distance  $d$  ahead of the vehicle, and it might need to process the distance  $d$  during each tenth or hundredth of a second, say. The amount of information to be processed appears to depend on  $d$  (not  $t^*$ ). Thus if information processing limits the performance of the system, performance will depend on  $d$  (not  $t^*$ ). Furthermore, suppose that the AEB system can use the result of a previous scan to help analyse the present scan. Assuming the scans are a constant time apart, then at higher speeds they will overlap less, there will be less similarity between them, and hence the previous scan will be less helpful. If anything, then, higher speed will tend to reduce the distance ahead that can be processed, not increase it.

Alternatively, suppose information processing is not the factor limiting performance. In this case, a limit of range might be necessitated by the desire to avoid false positive emergency braking. As a guide to a suitable value for this, it might be roughly the time needed to walk from one edge of the vehicle's path to the other, about 2.0 metres at about 1.4 m/sec, which is 1.4 sec. Thus in this case, there may be a time  $t^*$  instead of a distance  $d$ . An alternative to the obstacle moving out of the way is that the human driver may initiate braking or steering.

Suppose that an object is at a distance  $d$ , and that a time  $t^*$  is such that  $v \cdot t^* = d$ . Then  $t^*$  might be described as Time to Collision (TTC), and that term has been much used in the literature recently. I am not keen on this term, however, as it does not transfer well to the situation of one vehicle following another. The time  $t^* = d/v$  is the time to move distance  $d$  at constant relative speed  $v$ . In the vehicle-following context, danger arises from deceleration by the leading vehicle: relative speed does not remain

constant, and  $d/v$  overestimates the time available. That is, the error is in the unsafe direction. For a numerical example (in the context of possible use of such a time by the visual systems of human drivers), see section 11.5.2.

### 8.5.2 An impact, instead of a speed of impact

Suppose AEB operates as in model [A], but that all that can be observed or known is whether the vehicle strikes the obstacle or not. That is, impact speed is not known. This would be described as follows.

The vehicle is travelling at speed  $v$ . If there is an obstacle at a distance  $x$  directly ahead, it will be struck if  $\min\{x, d\} - v \cdot t < v^2/(2 \cdot a)$ .

Quantities  $d$ ,  $t$ , and  $a$  are respectively interpreted as a distance, a time, and a deceleration.

Hamdane et al. (2015) seem to have used the rule that a pedestrian is struck if  $x - 0.3 < v^2/(2 \cdot a)$ . They use metric units, that is, the distance 0.3 means 0.3 metres. The context for their work was reconstruction, for the purpose of understanding likely effectiveness of AEB systems, of pedestrian accidents that had been investigated in detail. Their sample of accidents was largely a low speed one (average vehicle speed was 40 km/h), so it is reasonable to omit  $d$ . Tracking of pedestrians might mean that  $t$  can be taken as 0.

### 8.5.3 Emergency braking may be unnecessary at low speeds

Emergency braking may be unnecessary at low speeds. Consider a challenge at a distance of 10 m. If the speed of the vehicle is 20 km/h (5.6 m/sec), for example, then in a reaction time of (say) 0.5 sec the vehicle would travel approximately 3 m, and decelerating at (say) 3 m/sec/sec would require only a further 6 m. A sophisticated AEB system may be able to either brake early and gently, or delay application of the brakes at the expense of needing to brake more sharply if the obstacle remains in the vehicle's path.

More generally, a model of the AEB system's decision-making (including brake or not, and perhaps with steering as an option) may one day be desirable, but it is excluded from the present description. It is not needed because the present concern is chiefly with deaths and serious injuries, and hence with fairly high speeds, and so the system needs to react strongly. Seiniger and Gail (2015) used such a model, and there will be an account of their results in section 11.2.

#### 8.5.4 Reaction time that varies with conditions

Concerning reaction time  $t$ , it is possible that this is very variable. Reasons for the variability of  $t$  might include lighting, weather, complexity of the scene (e.g., whether many objects, vehicles, and pedestrians were present), movement of components of the scene, the size and nature of the obstacle, and so on. Standardisation of test conditions is likely to mean that  $t$  should not be very variable in the test. Eventually it may be desirable to test an AEB system's responsiveness to a variety of complex conditions.

### 8.6 Discussion

It might be thought that measurement of reaction time  $t$  or distance available for braking  $y$  is sensible, and so is conduct of tests at various distances  $x$  and at various speeds  $v$ , but that  $d$  and  $t$  may not be appropriate concepts. If alternatives are sought, the model will need to specify how both  $y$  and  $t_{\text{obs}}$  (or alternative measurements) are related to  $x$ ,  $v$ , and whatever concepts are specified in place of  $d$  and  $t$ .

The point being made is that it is desirable that any test procedure should have clear implications for what will happen in other test conditions --- for example, with different  $x$  and  $v$ . It is very likely this will require a model of AEB operation, and a hypothesis that there are certain parameters of the AEB system that will remain constant in different conditions. The reasoning in this chapter suggests specific quantities to measure, parameters of an AEB system that should remain constant in different test conditions, and how these quantities may be used. If the model and the hypothesis turn out to be wrong, that is a positive step towards a better model.

If the model for behaviour is spelt out, it is likely to be possible to fit it to test data, understand the operation of AEB, and predict what will happen in other test conditions. A procedure to estimate the average real-world performance of an AEB system may be as suggested below. Symbols  $x$  and  $v$  refer to challenge distance and travelling speed (test conditions),  $t$  and  $d$  refer to reaction time and range (model parameters), and  $y$  and  $u$  refer to distance available for braking and impact speed (performance measures).

- There are three inputs: the test strategy, a model for the behaviour of the AEB system, and the joint distribution of  $x$  and  $v$ . (a) Sudden challenge at various  $x$  and  $v$  is suggested for the test. (b) The equation in section 8.4, utilising  $t$  and  $d$ , is suggested for the model. (c) Detailed investigation of accidents (in-depth at-scene crash investigation) is suggested as the source of the joint distribution of  $x$  and  $v$ .

- The test strategy will imply what the test measurements are.
- The model of the AEB system will imply how the test measurements are interpreted in terms of the AEB parameters.
- The joint distribution of  $x$  and  $v$  (that is, what combinations of  $x$  and  $v$  are observed in practice), together with the AEB parameters, will permit the distribution of  $y$  and the distribution of  $u$  to be calculated.

As mentioned earlier (section 6.3.3), some published trials suggest that most AEB systems have rather disappointing performance. Thus some aspects of what is proposed here may be premature. But, on the bright side, one of the vehicles tested by Hulshof et al. (2013) was able to stop from 50 km/h. (And it is likely that there have been subsequent improvements.) The meaning and testing of performance of AEB systems are likely to remain fluid for some time to come.

## 8.7 *Overview of chapters 6 - 8*

Chapter 6 is about AEB and how it is tested. Currently-popular methods of testing include the following.

- A physical target resembles a vehicle. The vehicle under test is driven towards the target at a steady speed. At low speeds, the AEB system is successful in stopping the vehicle. The test is repeated at increasing speeds until the vehicle fails to stop before the target.
- A target representing a pedestrian moves into the path of the vehicle under test. This type of test also is repeated at increasing speeds.

Methods involving plugging into the vehicle's electronics, and methods in which the vehicle is stationary, seem to be not used very much.

At the beginning of chapter 7, I express the opinion that the definition and measurement of the effectiveness of AEB is likely to be much easier if it is possible to unambiguously measure the time elapsing from a challenge by an obstacle to a command for emergency braking.

- The need to define the start of this period of time suggests the use of a sudden challenge, rather than a continuously-viewed obstacle.
- The need to define the end of this period suggests that access to the vehicle's internal communications (e.g., the communication between the AEB system and the braking system) will be needed.
- A time (a reaction time) or a distance (distance remaining that is available for braking) might be suitable quantities to measure.

The key points about the strategy of testing described in the previous paragraph, in which the start and end of a reaction time can be identified, are summarised below.

1. *To save lives, AEB systems need to have some effect at reasonably high speeds.* Reduction of impact speed may often be sufficient to save lives.
2. *Reaction at short distances and short times is important.* This suggests testing using some form of sudden challenge, but inference from tests with a continuously-viewed obstacle is a possibility.
3. *Emergency braking is the response needed.* Autonomous braking systems do have other uses also, as well as saving lives.
4. *The moment when emergency braking is commanded can be identified.* This is not necessary if it is desired to measure the performance of the whole vehicle rather than the AEB system alone.
5. *The problem of false positives is outside the scope of the discussion.* In order to overcome the problem of false positives, it may be necessary for AEB to operate only at very close distances.
6. *Characteristics of the AEB system are assumed to be reaction time and a range at which processing is triggered.* Measurement is made of the time elapsing from challenge until command for emergency braking.
7. *Distance available for braking is a measure of AEB effectiveness in given conditions.* Impact speed is a good alternative (it depends on deceleration also).
8. *It is desirable to be able to infer performance at all challenge distances and speeds.* Hence some theory of AEB performance is needed.

Points 6 - 8 refer to characteristics of AEB, distance available for braking, and inference about AEB performance for challenge distances and vehicle speeds not tested. The relevant equations, showing how measurements in a sudden challenge test may be utilised, are given in chapter 8.

The starting point for chapter 8 was the suggestion in section 5.2 (termed model [A]) as to how a vehicle or its driver might behave when it encounters an obstacle directly ahead. Some quantities are identified that it would be useful to measure --- time from challenge to reaction, distance available for braking, and impact speed. Equations are given for these outputs in terms of experimental conditions (that are known) and properties of the AEB system and the vehicle (that are unknown, and need to be estimated from experimental observations).

## 9. Interpretation of AEB test data: Testing without access to the vehicle's internal communications, and using a continuously-viewed obstacle

At this stage, a complete process has been proposed (section 8.6). Two further developments are desirable.

- Most present tests use measurements external to the vehicle (e.g., whether the vehicle stopped, stopping distances, impact speeds), and these reflect the AEB system plus brakes and tyres, rather than the AEB system alone.
- Most present tests use a continuously-viewed obstacle rather than one that appears suddenly.

The present chapter will adapt the method proposed in sections 8.3 and 8.4 in these two ways.

### 9.1 *Impact speed*

Of obvious attraction as a possible measure is the speed to which the vehicle has braked when it reaches the obstacle. Braking might be modelled as a lag of duration  $L$  (deceleration being zero during this lag) followed by maximum braking at constant deceleration  $a$ .

- As compared with the model in section 8.2, this has the advantage of introducing only a single extra parameter, the deceleration  $a$ . This is part of model [A], but the procedure in section 8.2 did not use it.
- The lag  $L$  is not an extra parameter because it is combined with  $t$  (the delay within the AEB system) to give the total delay. Consequently, three tests will be sufficient to estimate  $a$ ,  $t + L$ , and  $d$ . (The two delays,  $t$  and  $L$ , are not estimated. This has the advantage of simplicity, but sometimes not knowing them separately may be viewed as a disadvantage.)
- If the additional complication were felt to be justified, there could instead be a pure lag followed by linear ramp-up. Coelingh et al. (2010, p. 158) suggested a pure lag of 180 msec followed by a ramp of steepness 20 m/sec/sec/sec.

See also Hutchinson (2015a).

Instead of the equation in section 8.4, the equation will be:

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

An equation of the same general type is given in Rosén (2013, p. 622). Rosén's model includes an angle describing the field of view of the sensor,

a width referring to the field of view of the sensor, and a ramp-up time for the brakes. It also uses a time  $TTC_{max}$  instead of a distance  $d$  (and the same applies to the model of Seiniger et al., 2013). One can be converted to the other via  $TTC_{max} = d/v$ , but the reasoning given earlier (section 8.5.1) suggests use of a constant distance rather than a constant time.

Once  $t + L$  and  $d$  have been estimated, the above equation can be used to calculate impact speed  $u$  for any  $x$  and  $v$ . Deceleration  $a$  is also needed, of course. This might have been estimated for the specific vehicle, or a value common to all vehicles might be assumed (if it is desired to get a result that does not depend on tyres, road surface, etc.).

Probably of greatest interest are conditions in which it is borderline whether the AEB system works or not --- that is, the available distance is sufficient for the vehicle to start braking but not sufficient for it to stop. The following simpler equation then applies.

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

## 9.2 *Speed reduction and the shark's fin curve*

As well as  $u$ , the reduction in speed  $v - u$  and the proportionate reduction in speed  $(v - u)/v$  may also be of interest. These can be calculated via the equation for  $u$ . Some calculations of this type will be reported in chapter 13, for a variety of characteristics of an AEB system. For known characteristics (that is, known  $d$ ,  $t$ , and  $a$ ), more detailed examination could be made of the effect of different combinations of  $x$  and  $v$ . The results might be presented as a contour plot: the axes would be  $x$  and  $v$ , and the contours would show  $u$  or  $v - u$  or  $(v - u)/v$ . Among the most important features of such a plot would be the following two relations between  $x$  and  $v$ .

- The borderline of whether there is any braking at all,  $min\{x, d\} = v.(t + L)$ .
- The borderline of stopping,  $v^2 = 2.a.max\{0, min\{x, d\} - v.(t + L)\}$ .

Any such plot would assume specific values of  $d$ ,  $t + L$ , and  $a$ . The effect of changing any of these would be seen in comparing two or more such plots.

As a model of AEB operation, the equation in section 9.1 may be summarised as follows.

Emergency braking with deceleration  $a$  begins at a time  $t + L$  after there is a challenge within a distance  $d$  of the vehicle.

The equation in section 9.1 is closely related to the so-called shark's fin curve that several researchers have illustrated. Suppose the model of AEB operation is the following.

Emergency braking with deceleration  $a$  begins instantly when coming within a time  $t^*$  of an obstacle (that is, within a distance  $v \cdot t^*$ ).

This model has a time  $t^*$  instead of a distance  $d$ . For this model, the speed reduction is  $v - u$ , where  $u^2 = \max(0, v^2 - 2 \cdot a \cdot v \cdot t^*)$ . Plotting  $v - u$  versus  $v$  results in the shark's fin curve. An example is Figure 19 of Lemmen et al. (2013), in which  $a$  is 10 m/sec/sec and curves are shown for  $t^* = 0.5$  sec and 0.7 sec. The shark's fin curve in Coelingh et al. (2010) uses a model in which deceleration does not begin instantly, but after a delay and a ramp-up. Seiniger and Gail (2015), a paper that will be discussed in section 11.2, also illustrate the curve.

### 9.3 Use of measurements of times

For tests at distances less than  $d$ ,  $u^2 = v^2 - 2 \cdot a \cdot (x - v \cdot (t + L))$ , provided the vehicle does brake and distance is not sufficient for it to stop.

From three tests, it is desired to estimate  $d$ ,  $a$ , and  $t + L$ .

- Deceleration  $a$  can be found by standard methods of testing, though it might need to be checked that they are suitable for the present application. Or, as  $2 \cdot a$  is the rate of change of  $u^2$  with  $x$ , it can be found with two tests at the same  $v$ , by comparing  $u_1^2$  at distance  $x_1$  with  $u_2^2$  at distance  $x_2$ , provided  $x < d$  and  $x > v \cdot (t + L)$ .
- The time  $t + L$  may be found by subtracting the braking time  $(v - u)/a$  from the time between the challenge being made and the vehicle reaching the challenge point (at speed  $u$ ). There are two estimates of it, from the two tests at different distances. (If the vehicle does not reach the challenge point,  $t + L$  is found by subtracting the braking time  $v/a$  from the time between the challenge being made and the vehicle stopping.)
- The third test is conducted at a distance  $x_3$  that is sufficient to exceed  $d$ . The vehicle either reaches the challenge point or stops at time  $((x_3 - d)/v) + t + L + (v - u_3)/a$ ; the other quantities being known,  $d$  can be found.

Once  $t + L$  and  $d$  have been estimated, they can be used in the same way as described in section 8.6. For example, given a joint distribution of  $x$  and  $v$ ,  $t + L$  and  $d$  could be used to generate distributions of distance available for braking  $y$  and impact speed  $u$ .

### 9.4 Use of measurements of distances

The above does not require access to the communications between the AEB and braking systems. Indeed, suppose  $a$  can be found by standard methods in a first or preliminary test. In this case,  $t + L$  and  $d$  can be

found by the relatively coarse procedure of measuring distances (not times), provided that the vehicle's position at the moment of challenge can be identified, as will now be described.

In the second test,  $x < d$ . This test is used to find  $t + L$  via  $t + L = z_2/v - v/(2.a)$ , where  $z_2$  is the distance travelled from challenge to stop in this test. Section 9.5 will summarise the second test.

In the third test,  $x > d$ . This test is used to find  $d$  via  $d = x_3 - z_3 + v.(t + L) + v^2/(2.a)$  (where  $z_3$  is the distance travelled from challenge to stop in this test). Section 9.5 will summarise the third test.

The equation for the second test may be rewritten as  $z_2 - v^2/(2.a) = v.(t + L)$ . The equation for the third test may be rewritten as  $z_3 - v^2/(2.a) = x_3 - d + v.(t + L)$ . Consequently, they may be summarised as  $z - v^2/(2.a) = v.(t + L) + \max\{0, x - d\}$ . Thus if challenge distance is plotted horizontally and  $z - v^2/(2.a)$  is plotted vertically, the same general shape is observed, a line of slope 0 and then a line of slope 1.

The two lines intersect at challenge distance =  $d$  and  $z - v^2/(2.a) = v.(t + L)$ , permitting the two unknowns ( $d$  and  $t + L$ ) to be estimated.

As noted in section 8.3, testing is difficult, real data is nearly always messy, and neat straight lines of slopes 0 and 1 are not likely in practice. Nevertheless, it should be possible to obtain values of  $d$  and  $t + L$  that best fit the data.

## 9.5 *Summaries of tests: What happens when and where*

The first or preliminary test is to measure  $a$ .

The second and third tests need to be conducted in such a way that the vehicle can pass through the challenge point without anything being damaged. In the following sequences of events, it is assumed that emergency braking does occur and the vehicle does stop.

Consider what has been labelled the second test, which is at a challenge distance ( $x_2$ ) that is less than  $d$ .

- *The range is reached.* Speed is  $v$ . Distance from the challenge point is  $d$ . (A challenge has not been made yet.)
- The vehicle continues at speed  $v$ .
- *The challenge is made.* Speed is  $v$ . Distance from challenge point is  $x_2$ . Time after the challenge is 0.
- The vehicle continues at speed  $v$ .
- *Emergency braking starts.* Speed is  $v$ . Distance from the challenge point is  $x_2 - v.(t + L)$ . Time after challenge is  $t + L$ .

- *The vehicle stops.* Speed is 0. Distance from the challenge point is  $x_2 - v.(t + L) - v^2/(2.a)$ . Time after challenge is  $(t + L) + v/a$ .

Now consider a test at a challenge distance ( $x_3$ ) that is greater than  $d$ .

- *The challenge is made.* Speed is  $v$ . Distance from challenge point is  $x_3$ . Time after the challenge is 0.
- The vehicle continues at speed  $v$ .
- *The range is reached.* Speed is  $v$ . Distance from the challenge point is  $d$ . Time after challenge is  $(x_3 - d)/v$ .
- The vehicle continues at speed  $v$ .
- *Emergency braking starts.* Speed is  $v$ . Distance from the challenge point is  $d - v.(t + L)$ . Time after challenge is  $(x_3 - d)/v + (t + L)$ .
- *The vehicle stops.* Speed is 0. Distance from the challenge point is  $d - v.(t + L) - v^2/(2.a)$ . Time after challenge is  $(x_3 - d)/v + (t + L) + v/a$ .

### ***9.6 Testing using a continuously-viewed obstacle: Speed $v$ as the principal independent variable***

So far, it has been convenient to suppose that the obstacle or target appeared suddenly, but the model can be used with a continually-present obstacle or target.

The principal meaning of  $t + L$  is the delay between an obstacle appearing close to the vehicle and braking commencing. (Here and in later paragraphs, suitable changes need to be made if a test of the type described in section 8.3 is conducted:  $t + L$  is replaced by  $t$ , commencement of braking is replaced by command for braking, and so on.)

The time  $t + L$  also has another meaning. Consider obstacles far from the vehicle (that is, beyond the range  $d$ ). The distance from the obstacle at which braking commences is  $d - v.(t + L)$ . If this distance can be measured,  $t + L$  and  $d$  can be inferred by plotting it versus  $v$ :  $t + L$  equals the change in distance divided by the change in speed, for example. This assumes that speed is sufficiently high that braking is necessary immediately the range is reached.

The basis of the model being used (section 9.1) is that there is a moment at which sensing or processing of an obstacle first occurs. If this is valid, then it is a straightforward idea that it occurs at a distance  $d$  given by the distance from commencement of braking to the obstacle plus the distance  $v.(t + L)$  lost in reacting, whether this reaction is most appropriately described as sensing or processing or operating.

## 10. Data from AEB testing by Hulshof et al. (2013)

It seems likely that a quick reaction will be important in saving lives and serious injuries. Consequently, direct measurement of reaction using a sudden challenge is desirable. The data in Hulshof et al. (2013) is not of that form, but nevertheless will be analysed to suggest values of  $t + L$  and  $d$  for several AEB systems. Some mention of the data has already been made in section 6.3. The vehicle under test was driven directly towards a dummy car, the procedure being similar to that described in section 6.2.3. A short account of some of the results in this chapter is in Hutchinson (2016).

Performance of the AEB systems tested by Hulshof et al. was fairly promising. However, it should be remembered that the speeds in these tests were only 50 km/h and under. Also, the chief purposes of the systems may have been different from what I have in mind: for example, there may have been emphasis on avoiding low-speed impacts, rather than on saving lives at high speeds.

The tests were made a number of years ago, and the various AEB systems may have improved in performance since then. The chief point of this chapter is to demonstrate the method of data analysis, and that (in principle) this permits inference about properties of the AEB system.

### 10.1 *Data, summary statistics, and organisation of results*

#### 10.1.1 Description of the data

The data takes the form of plots of cars' speeds versus time, with time = 0 corresponding to the car either striking the target or stopping.

- Speed is at first constant, then decreases to zero if the car succeeds in stopping before the obstacle. (This occurs at low speeds such as 20 km/h.)
- Or speed may decrease to a non-zero value if the car slows but still strikes the obstacle.
- Or it may not decrease at all, if the car either does not detect the obstacle or does not react sufficiently quickly. (This occurs at relatively high speeds such as 50 km/h.)

There were eleven cars driven at a stationary target, mostly at eight speeds between 10 km/h and 50 km/h. (The target was something that is supposed to look like a car to the sensors of an AEB system.)

### 10.1.2 Extraction of descriptive measurements

For each test, the data consists of a plot of the car's speed versus time. Some descriptive measurements need to be obtained from that.

Perhaps the most obvious ones are the time at which braking commenced and the speed at impact. (Impact speed may be zero if the car succeeds in stopping before the obstacle, or the original speed if there was no braking, or something in between.)

Those are not ideal, however, as they are affected by how severe the deceleration was, which is affected by the car's brakes and tyres. What will be used below is the distance from the target at which braking commenced. An alternative is this distance divided by the speed  $v$ : this is the time from the target at which braking commenced (the time if no braking took place, that is).

As there is no sudden challenge, there is no defined start time, and the only fixed time is when either an impact occurs or the car stops. The distance of the car from the obstacle when braking commences is not given by Hulshof et al. There are some difficulties in estimating it from the plots.

- If the car stopped before the obstacle, the data will not be used when estimating  $t + L$ . This is for two reasons. (a) At low speeds there may have initially been no braking because it was not necessary; thus commencement of braking occurs after, not coincidentally with, time  $t + L$  after reaching the trigger point. (b) The distance of the car from the obstacle when the car stops is not given. (This is less important as the distance is probably small and can be neglected.)
- Tests in which the car did not brake provide little information.
- Thus tests in which the car braked but nevertheless struck the obstacle are the most interesting: in such cases, the AEB system is facing a task close to its limit of performance.
- For simplicity, the quantity estimated below is the distance at which braking started. There are at least two alternatives that might throw further light on AEB operation. (a) The distance at which maximum braking started. (b) Supposing that all braking was maximum braking, the distance at which this would have occurred in order to give the observed impact speed.

Some approximate results can nevertheless be obtained. These improve on the simple idea that the highest speed at which there is any braking is an estimate of  $d/(t + L)$ .

### 10.1.3 How the results will be organised

For each relevant test, I will describe how I read the plot that Hulshof et al. give. Then I will interpret the set of tests referring to a model of car tested at several speeds. This will make it easy to check my findings, should that be desired.

Models of car with LIDAR sensors will be considered in section 10.2. Models of car with other sensors will be considered in section 10.3.

### 10.1.4 Interpretation

From section 9.6, the distance at which braking commences must be the distance at which braking was commanded minus the distance travelled during the time  $t + L$ .

Braking is commanded at distance  $d$ . A change in the distance at which braking commences equals the change in speed multiplied by time  $t + L$ . The unknown quantity  $t + L$  must equal the ratio of change in distance to change in speed.

## 10.2 *Eight models of car with LIDAR sensors*

### 10.2.1 Mazda 6

*20 km/h.* Braking commenced about 1.2 sec before the car stopped, deceleration was approximately constant (about 5 m/sec/sec). It can be calculated that distance travelled during deceleration was about 3 m. The distance from the target at which the car stopped is not given, but was probably small, so the distance at which braking commenced was a little over 3 m from the target.

*25 km/h.* Braking commenced about 0.6 sec before the car struck the target at about 8 km/h, deceleration was initially about 7 m/sec/sec and later about 10 m/sec/sec. Distance travelled during deceleration was about 3 m. Thus the distance at which braking commenced was about 3 m.

*30 km/h.* There was no braking before the car struck the target at 30 km/h.

*Interpretation of the set of tests.* The increase of speed from 6.9 m/sec (25 km/h) to 8.3 m/sec (30 km/h) was enough to overcome the distance of 3 m that occurred at the lower speed. Thus  $t + L$  must be bigger than 3/1.4, that is, bigger than about 2 sec. If  $t + L$  is 2 sec, for example,  $d$  is about 17 m (calculated from 25 km/h for 2 sec, plus the 3 m travelled during

deceleration). Or if  $t + L$  is 3 sec,  $d$  is about 24 m. (An alternative interpretation will be noted in section 10.4, that the AEB system switches itself off above some speed.)

### 10.2.2 Volvo XC60

*20 km/h.* Braking commenced about 0.8 sec before the car stopped, deceleration was about 7 m/sec/sec. Distance travelled during deceleration was about 3 m. The distance from the target at which the car stopped is not given, but was probably small, so the distance at which braking commenced was a little over 3 m from the target.

*25 km/h.* Braking commenced about 0.6 sec before the car struck the target at about 12 km/h, deceleration was initially about 4 m/sec/sec and later about 8 m/sec/sec. Distance travelled during deceleration was about 3 m. Thus the distance at which braking commenced was about 3 m.

*30 km/h.* Braking commenced about 0.3 sec before the car struck the target at about 25 km/h, deceleration was about 5 m/sec/sec. Distance travelled during deceleration was about 2 m. Thus the distance at which braking commenced was about 2 m.

*35 km/h.* Braking commenced about 0.2 sec before the car struck the target at about 32 km/h, deceleration was about 4 m/sec/sec. Distance travelled during deceleration was about 2 m. Thus the distance at which braking commenced was about 2 m.

*40 km/h.* Braking commenced about 0.2 sec before the car struck the target at about 38 km/h, deceleration was about 2 m/sec/sec. Distance travelled during deceleration was about 2 m. Thus the distance at which braking commenced was about 2 m.

*45 km/h.* Braking commenced about 0.1 sec before the car struck the target at about 44 km/h, deceleration was about 3 m/sec/sec. Distance travelled during deceleration was about 1 m. Thus the distance at which braking commenced was about 1 m.

*50 km/h.* There was no braking before the car struck the target at 50 km/h.

*Interpretation of the set of tests.* In this case, there is enough data to compare two speeds at which the car braked but not sufficiently to stop. The increase of speed from 6.9 m/sec (25 km/h) to 12.5 m/sec (45 km/h) corresponded to a reduction in distance from 3 m to 1 m. Thus  $t + L$  is about  $2/5.6$ , that is, about 0.4 sec. Further,  $d$  is about 6 m (calculated either from 25 km/h for 0.4 sec, plus the 3 m travelled during deceleration, or from 45 km/h for 0.4 sec, plus the 1 m travelled during deceleration). As

the distance from the target at which braking commenced decreased with increasing speed, the corresponding time (i.e., the ratio of this distance to speed  $v$ ) did also.

### 10.2.3 Other models of car

Results for five other cars with LIDAR sensors were broadly similar (but not identical) to those of the Mazda 6. Results for a Volvo V40 with a LIDAR sensor were similar to those of the Volvo XC60. There will be some interpretation of the difference between these two groups of cars in section 10.4 below.

## 10.3 *Three models of car with other sensors*

### 10.3.1 Mitsubishi Outlander (RADAR)

*20 km/h.* Braking commenced about 0.9 sec before the car stopped, deceleration was initially about 4 m/sec/sec and later about 8 m/sec/sec. Distance travelled during deceleration was about 3 m. The distance from the target at which the car stopped is not given, but was probably small, so the distance at which braking commenced was a little over 3 m from the target.

*30 km/h.* Braking commenced about 1.5 sec before the car stopped, deceleration was initially about 3 m/sec/sec and later about 7 m/sec/sec. Distance travelled during deceleration was about 7 m. The distance from the target at which the car stopped is not given, but was probably small, so the distance at which braking commenced was a little over 7 m from the target.

*35 km/h.* There was no braking before the car struck the target at 35 km/h.

*Interpretation of the set of tests.* The increase of speed from 8.3 m/sec (30 km/h) to 9.7 m/sec (35 km/h) was enough to overcome the distance of 7 m that occurred at the lower speed. Thus  $t + L$  must be bigger than  $7/1.4$ , that is, bigger than about 5 sec. If  $t + L$  is 5 sec, for example,  $d$  is about 49 m (calculated from 30 km/h for 5 sec, plus the 7 m travelled during deceleration). Or if  $t + L$  is 6 sec,  $d$  is about 57 m.

### 10.3.2 Volvo V40 (CADS III+, which is RADAR, camera, and LIDAR)

*20 km/h.* Braking commenced about 0.8 sec before the car stopped, deceleration was initially about 6 m/sec/sec and later about 9 m/sec/sec. Distance travelled during deceleration was about 2 m. The distance from the target at which the car stopped is not given, but was probably small, so the distance at which braking commenced was a little over 2 m from the target.

*30 km/h and 35 km/h.* The car also stopped at these speeds.

*40 km/h.* Braking commenced about 0.9 sec before the car struck the target at about 12 km/h, deceleration was initially about 6 m/sec/sec and later about 10 m/sec/sec. Distance travelled during deceleration was about 7 m. Thus the distance at which braking commenced was about 7 m.

*45 km/h.* Braking commenced about 1.0 sec before the car struck the target at about 16 km/h, deceleration was initially about 5 m/sec/sec and later about 10 m/sec/sec. Distance travelled during deceleration was about 9 m. Thus the distance at which braking commenced was about 9 m.

*50 km/h.* Braking commenced about 0.9 sec before the car struck the target at about 25 km/h, deceleration was initially about 7 m/sec/sec and later about 8 m/sec/sec. Distance travelled during deceleration was about 9 m. Thus the distance at which braking commenced was about 9 m.

*Interpretation of the set of tests.* This data is not compatible with the model being used. Firstly, at 40 km/h, the car starts braking closer to the target than at 45 km/h or 50 km/h (and this cannot be because there is sufficient distance to stop, because this is not the case). A possible explanation is that there are two contributing reasons,  $t + L$  being very small and there being appreciable random variation in braking distances. If  $t + L$  is 0.0 sec,  $d$  is about 8 m. Secondly, at 50 km/h the car does not brake as sharply as it should.

### 10.3.3 Subaru Outback (stereo camera)

*20 km/h and 30 km/h.* The car stopped at these speeds.

*52 km/h.* Braking commenced at least 2.0 sec before the car stopped, deceleration was initially about 3 m/sec/sec, later about 9 m/sec/sec, and finally about 5 m/sec/sec. Distance travelled during deceleration was about 15 m. The distance from the target at which the car stopped is not given,

but was probably small, so the distance at which braking commenced was a little over 15 m from the target.

*Interpretation of the set of tests.* Evidently  $d$  is at least 15 m (equivalent to 1.1 sec at the speed of 50 km/h), but otherwise performance is sufficiently good --- that is,  $d$  is sufficiently great and/or  $t + L$  is sufficiently small --- that there is little information about  $t + L$  or  $d$ . Hulshof et al. do not comment on what they might know or surmise about the false alarm frequency achieved, but presumably it is acceptably low.

Table 10.1. Summary of the interpretation of results of Hulshof et al. (2013) in terms of  $t + L$  and  $d$ .

Car and sensor	$t + L$ , and $d$
Mazda 6 (LIDAR)	at least 2 sec, and at least 17 m
Volvo XC60 (LIDAR)	about 0.4 sec, and about 6 m
Mitsubishi Outlander (RADAR)	at least 5 sec, and at least 49 m
Volvo V40 (RADAR + camera + LIDAR)	about 0.0 sec, and about 8 m
Subaru Outback (stereo camera)	(not known), and at least 15 m

#### 10.4 Comparison of models of car

Table 10.1 summarises results for the five models of car.

- The calculated values of  $t + L$  and  $d$  for the Mitsubishi Outlander appear unusual. The key feature of the speed graph for this vehicle is that at 30 km/h, braking commenced about 1.5 sec before it stopped, and at 35 km/h there was no braking. The present interpretation is that the extra 1.4 m/sec (5 km/h) used up all of the distance that was evidently available at 30 km/h, some 7 m. Any competing model or theory needs to explain what appears to be a surprising contrast between what happened at 30 km/h and what happened at 35 km/h. A possibility, which also applies to the Mazda 6 and cars with similar performance patterns, is that the AEB system switches itself off above some (quite low) speed; but I think Hulshof et al. would have noted this if they thought it at all likely.

- The Volvo V40 with the CADS III+ option performed second best of the eleven cars, but when considered in detail the results were somewhat surprising, as discussed earlier (section 10.3.2).
- The Subaru Outback performed best of the eleven cars. Indeed, 50 km/h was not fast enough to reach its limit and give estimates of  $t + L$  and  $d$ .

Considering the eight cars with LIDAR sensors, differences can be seen between the speed graphs of the six non-Volvo cars on the one hand and those of the two Volvo cars on the other: at speeds in the range 35 km/h to 45 km/h the others do not brake but the Volvos do start to brake (suggesting that the Volvos are the best of this subset of cars), and the distinction is reinforced because at 25 km/h, three of the six other cars stop but the Volvos do not (suggesting relative poor performance by the Volvos). Thus it is not the case that the contrast seen in Table 10.1 is some artificial consequence of the calculations. The difference between the speed graphs has transformed into different values of the parameters of the AEB systems. The other models of car have a long range but also a long reaction time, whereas the Volvos have a short range but also quick reaction.

Hulshof et al. (p. 10) were aware in general terms of differences within the group of cars having LIDAR sensors. However, two clarifications of their comments are needed.

- They noted that braking occurs earlier as speed increases from 10 km/h to 25 km/h. What may be happening is that quick emergency braking is not required at low speeds, and the AEB system is sophisticated enough to attempt to strike a balance between early braking that might turn out to be unnecessary and late braking that might need to be severe.
- Hulshof et al. focus on the distinction between cars that at 25 km/h avoid the obstacle and those that strike it. This groups the Mazda 6, the Mazda CX-5, and the Ford Focus with the two Volvos, as these all failed to avoid at 25 km/h. According to the present discussion, the main distinction is instead between cars that show some reaction at speeds of 35 km/h to 45 km/h (i.e., the two Volvos) and those that do not (the other six cars).

## ***10.5 Discussion***

There were several tests in which the car did brake but not with sufficient deceleration to stop before striking the target. In these cases, improving the brakes and tyres to give quicker ramp-up of deceleration to the maximum possible might translate directly to reduced impact speed. This is particularly evident for those tests for which braking started very late and the maximum deceleration was quite low. See Eckert et al. (2013, p. 7) for some evidence of progress with improving brakes.

If the possibility can be dismissed that the AEB system switches itself off at the higher speeds, the speed plots of Hulshof et al. are relevant to the issue of a time range  $t^*$  versus a distance range  $d$  (see section 8.5.1). If there is a time range  $t^*$ , emergency braking commences at a time  $t^* - t$  before the vehicle would strike the obstacle if there were no braking. There is no degradation of this aspect of performance with increasing speed. (Although distance available is  $v.(t^* - t)$  and this increases with speed, the braking distance required to stop increases with the square of speed, and stopping does not occur at high speed.)

- In contrast to the prediction that at all speeds there will be some braking, most vehicles tested failed to brake at speeds of 35 km/h and over. This suggests there is a distance range, not a time range.
- The Volvo V40 with CADS III+ (RADAR, camera, and LIDAR) is an exception. An explanation was suggested in section 10.3.2 for the data. Nevertheless, the data is more suggestive of a time  $t^*$  rather than a distance  $d$ .
- The very good performance of the Subaru is compatible with either a distance range or a time range.

Experimentation is difficult, and there may be miscellaneous inaccuracies either in the data of Hulshof et al. or in how I have processed it. Thus some of the detail in this chapter may be overinterpretation by me, and some of the figures in Table 10.1 could be badly wrong. Perhaps more seriously, someone reading this may know how AEB systems really work, and be able to say that model [A] is unrealistic. But I am not sure that would upset me. For one thing, I could look forward to them writing a more realistic account than I have given. For another, my opinion is that the priority is to make optimal use of experimentation by relating performance measures to choices about the test ( $v$  and  $x$ ) and to operational characteristics of the system (possibly  $d$  and  $t$ , or possibly something else); being correct about details of AEB operation is a lower priority.

## ***10.6 Overview of chapters 9 and 10***

At present, most tests use measurements external to the vehicle, rather than plugging into a vehicle's electronics. Chapter 9 obtained equations applying to this type of test. The time duration appearing in those equations is different from what was relevant earlier: it is the sum of the reaction delay and a lag in brake operation.

Chapter 9 also described how the equations may be adapted to an experiment in which the obstacle is continuously in view, as it is when the vehicle under test is driven directly towards a stationary obstacle.

Test data published by Hulshof et al. (2013) using a continuously-viewed obstacle was re-examined in chapter 10. Considering the eight cars with LIDAR sensors, differences were identified between the six non-Volvo cars on the one hand and those of the two Volvo cars on the other. The two groups of cars seem to have different values of the parameters of the AEB systems. The non-Volvo cars have a long range but also a long reaction time, whereas the Volvos have a short range but also quick reaction. The tests were made a number of years ago, and the various AEB systems may have improved in performance since then. The chief point of the chapter is to demonstrate the method of data analysis, and that (in principle) this permits inference about properties of the AEB system.

I think that, in view of the probable great importance of a quick reaction in saving lives and serious injuries, it would be unwise to rely upon a continuously-viewed obstacle for indirect estimation of reaction time: direct measurement of reaction using a sudden challenge is desirable.

## 11. Discussion of AEB testing and the resulting data

This is a chapter of odds and ends of discussion.

As a follow-up to the consideration of data in chapter 10, sections 11.1 and 11.2 will examine two more sets of data.

Then section 11.3 discusses weak braking as a possible action of an autonomous system, section 11.4 argues that a variety of methods of testing is desirable, and section 11.5 summarises some theory developed in the context of human drivers. Section 11.6 notes the limited scope of theories in the style of model [A]. Section 11.7 sketches how, in principle, a system of testing might operate if operation of AEB is complicated and differs between cars.

### 11.1 *Oikawa et al. (2014)*

#### 11.1.1 Background

Oikawa et al. (2014) have reported some AEB test results.

- Their attitude seems similar to mine --- they want to understand how an AEB system works by testing it.
- The dimensions of the vehicle tested are consistent with it being a Subaru Legacy station wagon, and its date is given as January 2010.
- Oikawa et al. used a dummy pedestrian. Hulshof et al. (2013) used a dummy car.
- Oikawa et al. reported collision speeds at test speeds of 20, 30, 40, 50, and 60 km/h (each being the average of several tests).
- Model [A] (section 8.1) refers to an obstacle "directly ahead". This phrase is supported by some tests with different positions of the dummy pedestrian conducted by Oikawa et al.
- But in other respects, Oikawa et al. do not seem to have anything analogous to model [A].

#### 11.1.2 Results

Now consider the results in Oikawa et al. (2014).

- At test speeds of 20, 30, 40, 50, and 60 km/h, average collision speeds were 3.5, 15.0, 6.3, 17.0, and 34.3 km/h.
- Collision speed was higher at 30 km/h than at 40 km/h. I am inclined to ignore the low speed results. They may be due to the system not going into full emergency mode at low speeds. At 40

km/h, there is evidence of two distinct strengths of braking, both being appreciably less than the maximum possible, in Figure 7 of the related paper by Matsui et al. (2011).

- Oikawa et al. do not give speed versus time curves for the braking period. They simply claim braking of 8.5 m/sec/sec and show in an example a ramp-up of about 0.4 sec.
- Using deceleration of 8.5 m/sec/sec and assuming ramp-up time is zero gives braking distances of 7.1, 10.1, and 11.1 m at the three highest test speeds (40, 50, 60 km/h).
- Using deceleration of 8.5 m/sec/sec and making an allowance for ramp-up gives braking distances of perhaps 9.1, 12.7, and 14.3 m at the three highest test speeds.

It may be noted that Hulshof et al. (2013) reported rather better performance by a Subaru Outback, that is, it stopped from 52 km/h.

### 11.1.3 Interpretation

The results of Oikawa et al. suggest that the higher the speed, the greater was the distance from the obstacle when braking commenced. This is inconsistent with model [A].

However, 40 km/h may be a low speed at which the system does not react as strongly as it should. The distances at 50 and 60 km/h (13.9 and 16.7 m/sec) are not very different. If reaction time were 0.4 sec (for example), distance travelled during the reaction time would be 5.6 and 6.7 m at the two speeds. Total distances during the reaction time and braking would thus be  $12.7 + 5.6 = 18.3$  m at 50 km/h and  $14.3 + 6.7 = 21.0$  m at 60 km/h. These are both estimates of the range  $d$ . Perhaps the difference is random variation.

Oikawa et al. did not give the braking curves, and so I have had to use the deceleration figure of 8.5 m/sec/sec. Deceleration at 60 km/h may perhaps have been stronger than at 50 km/h.

It may be suggested that if a car is driven towards a stationary obstacle, the braking distance should be obtained (either by calculation or by observing the brake lights). Then concerning the operation of AEB, a plot of braking distance versus test speed is more informative than plotting impact speed versus test speed.

## ***11.2 Seiniger and Gail (2015)***

### **11.2.1 Introduction**

The method of testing considered here was as in (or perhaps very similar to) Schram et al. (2015) (see section 6.2.4). Seiniger and Gail (2015) had both a detailed model of AEB operation, and real test results from several cars with different AEB systems. Much, though not all, of the paper, concerns pedestrian accidents. The model is embodied in a simulation system. Parameters of the model can be adjusted to the different AEB systems in different cars. There are several categories of parameter: brake strategy, sensor characteristics, and brake hardware.

Is it possible to describe the model in simple terms similar to model [A] of section 8.1? The model was not given an explicit description by Seiniger and Gail, but it is not clear that is impossible. It might be possible to handle complicated operation of the sensor by phrasing the description as "If the sensor detects an obstacle" rather than "If there is an obstacle". (The sensor would then require separate description.)

### **11.2.2 Results**

Figure 4 of Seiniger and Gail (2015) compares simulation results and test results, there being four cars each tested in four variants of the pedestrian test, and the speeds being between 10 km/h and 60 km/h. What is shown in that Figure are plots of speed reduction versus test speed. (I do not think that speed reduction is the most suitable quantity for plotting, but it nevertheless can be discussed.)

- Apparently the parameter values were chosen so that the simulation results fitted the test results.
- For some cars, the AEB system was fully successful (i.e., impact was avoided) in easy conditions (that is, at speeds of 20 or 30 km/h in one or more variants of the test). The simulation was successful in describing this.
- For most cars at 60 km/h in most variants of the test, there was some reduction of speed before impact. The simulation had some success in describing this, but quite often predicted performance to be better than it was.
- The opinion of Seiniger and Gail was that "Simulation results match test data sufficiently well".

### 11.2.3 Comments on simulation results

In this section, most interest is in the simulation. The performance of the AEB systems is background to how that was predicted by the simulation. My opinions are as follows.

- All cars performed quite poorly in the variant of the test representing a child pedestrian. The simulation predicted performance to be better than it was. It seems possible to me that this failure might be remedied by quite a minor improvement to the simulation of the sensor, without altering the most important aspects of the rules the simulation is obeying.
- With parameter values being chosen to fit the test results, it is easy to predict fully successful performance. Successful prediction of successful performance does not count for much.
- What is difficult is, in addition, predicting breakdown of performance in more difficult conditions. Four cars, each with three variants of adult pedestrian test, means there are 12 relevant plots. Omit the two for which there was no breakdown of performance at the higher speeds, and 10 plots remain. The simulation is quite a good predictor of the breakdown of performance in 8 of these cases.

### 11.2.4 Testing viewed abstractly

I believe in the usefulness of models, like model [A] and like that of Seiniger and Gail, that attempt to represent what is really happening. (Of course there can be debate about simplicity versus complexity.)

Despite this, I think it interesting to consider the success or failure of the AEB system from the viewpoint of a simple generic model of testing in the abstract, a model that does not draw on special knowledge of AEB. See Appendix 3 for this.

Looking at the plots in Figure 4 of Seiniger and Gail, it seems to me that the simple generic model, with a very small number of parameters, is a good fit to the AEB test data. The point of this is to put into perspective the success of the simulations of Seiniger and Gail. The specifics of the simulations are not impressive if a generic model is a good fit.

## 11.3 *Weak braking*

In chapters 6 - 10, the view has been taken that to save lives and serious injuries, AEB will need to command very strong braking. This is because in order to avoid false positives, the response will need to be made late; because it is late, braking will need to be severe. The following

paragraphs will suggest an alternative strategy: to make false positives acceptable by making the response a weak one.

If an obstacle is detected 3 m (for example) directly ahead of a vehicle travelling at 60 km/h, emergency braking appears plainly necessary. In contrast, if the obstacle is at a distance of 30 m, the appropriate response is not so apparent. The distance corresponds to 1.8 sec at 60 km/h; if lateral movement of 1 m is sufficient to take the obstacle out of the vehicle's path, this would require only 0.7 sec at 1.4 m/sec (walking speed).

As the obstacle may be out of the vehicle's path in a fraction of a second, a false positive seems quite likely; sharp braking of 5 m/sec/sec would be required to stop within 30 m, and this is probably inappropriate. But if braking is only weak (1 m/sec/sec or 2 m/sec/sec), a false positive might not be dangerous or upsetting to drivers. As example of such a model is in Kim et al. (2015).

Thus it is worth calculating what might be the effect of weak braking, as follows.

- Suppose there is 1.5 sec of braking at 1 m/sec/sec. The consequence is that 60 km/h is reduced to 55 km/h and the distance from the obstacle is now 6 m.
- Suppose the obstacle is still present, and emergency braking of 8 m/sec/sec now begins. The obstacle is struck at about 11.6 m/sec.
- If, on the other hand, the vehicle had been travelling at 60 km/h when emergency braking of 8 m/sec/sec began at a distance of 6 m, the obstacle would have been struck at the faster speed of 13.5 m/sec.

The reduction of impact speed is worthwhile.

The equation in section 9.1 could be used on the assumption that braking would be weak rather than as strong as possible. That is, the following model of AEB operation would be used.

Braking with deceleration  $a$  begins at a time  $t + L$  after there is a challenge within a distance  $d$  of the vehicle.

The wording is only a little different from that used earlier (section 9.2), but now it is presumed that  $a$  is small and that (because false positives are now assumed to be not dangerous or upsetting and thus may be relatively frequent)  $t + L$  is small and  $d$  is large.

Furthermore, the model could be generalised (if the additional complexity were justified) by  $d$  and  $t$  having certain values in respect of emergency braking, and different values in respect of weak braking. It is possible to derive equations for impact speed  $u$  (more complex than those given earlier, of course) for such a model. Of course, the model cannot say whether occurrence of false positive weak braking would or would not be acceptable to drivers. However, it should be able to estimate how much benefit weak braking would give, in terms of reduced impact speeds.

## ***11.4 Methods of testing AEB systems***

Testing of AEB systems is at quite an early stage of development. Future test protocols may be different from present ones.

- A variety of types of testing need to be experimented with, as AEB is likely to save lives, and it is important that as much benefit is gained as soon as possible.
- Having one or more models expressed as equations makes it possible to understand AEB performance and extrapolate to conditions not directly tested.
- A test conducted for regulatory or consumer-information purposes is standardised, in order to be fair to all the different items (vehicles, in this case) being tested. But a standardised test should be complemented by experimentation with alternatives, when analysis, understanding, and inference are important, as they are at present.
- It can be expected that data on the results of testing using various methods will be published. I hope people will be able to adapt the methods of data analysis that are implied by the equations given in earlier chapters to the data published in future.

At present, methods of testing are used in which collision between the vehicle and an obstacle, with the possibility of damage to either, sometimes occurs. Testing is particularly valuable at speeds that are difficult for present-day AEB systems. Thus it is likely that there will indeed be tests in which there is collision with (rather than avoidance of) the obstacle. This makes me think it desirable that alternative methods be available.

An AEB system that is only partially effective --- in the sense that  $d$  is quite small and  $t + L$  is quite large --- is likely to nevertheless be very effective in saving lives and serious injuries, largely by mitigation of crashes rather than avoidance. If that is so, it is important that a testing procedure should encourage early adoption of AEB (while, of course, encouraging the improvement of AEB). Reduction of impact speed may be achieved by improvements to braking systems and tyres, as well as by AEB. The results of some types of test are affected by the brakes and tyres as well as by the AEB system.

## ***11.5 Human drivers***

It is possible that model [A] or something similar might apply to human drivers. I think that such models have been not very common in the literature on human driving. An important part of my case in favour of

such models is that impact speed is very important, therefore even a little earlier reaction or greater strength of braking is potentially life-saving, therefore a model relevant to only the last few moments before impact is nevertheless likely to be useful.

Two papers from the psychology of perception will be discussed in this section.

### 11.5.1 Lee (1976)

The following is based on Lee (1976, p. 443).

- Consider a vehicle approaching a stationary obstacle at speed  $v$ . Suppose that the driver's braking reaction begins when time-to-collision is  $\tau_m$ , and that time  $t_f$  elapses before the driver reacts and appropriate deceleration is reached.
- The distance from the obstacle is approximately  $(\tau_m - t_f).v$ . The constant deceleration required to stop before collision is  $\frac{1}{2}.v/(\tau_m - t_f)$ .
- It might be that  $\tau_m$  is independent of speed  $v$ . (And from its definition, it is natural to presume that  $t_f$  is almost independent of  $v$ .) Deceleration will then need to be stronger, the higher that speed is.

If  $x$  is the distance to an obstacle and  $v$  is speed, the time to reach the obstacle ( $\tau$ , often referred to as Time to Collision, TTC) is  $x/v$ . The distance required to stop from a given speed  $v$  at constant acceleration  $a$  is  $v^2 / (2.a)$ . If it is assumed that a vehicle can maintain its present deceleration, then it will be able to stop before collision if  $x > v^2 / (2.a)$ . Notice that  $a$  is positive even though it is a deceleration. Lee (1976) transformed this inequality into a condition on  $\tau$ .

- Consider the rate of change of this:  $\tau' = (x'.v - x.v') / v^2$ .
- It is necessary to be careful with the signs of the variables:  $x$  and  $v$  are both considered positive, but the vehicle is approaching the obstacle and thus  $x$  is decreasing, therefore  $x'$  must be  $-v$ , not  $v$ , and  $x'' = -v' = a$ , positive for deceleration.
- Thus  $\tau' = (-v^2 + x.a) / v^2$ , that is,  $\tau' = -1 + x.a / v^2$
- The condition to be able to stop before collision,  $x > v^2 / (2.a)$ , means that  $x.a / v^2 > \frac{1}{2}$ . That is,  $\tau' > -\frac{1}{2}$ .

This is important because it is reasonable to suppose that information on  $\tau$  and  $\tau'$  is available in the human visual system.

### 11.5.2 Stewart et al. (1993)

The following is based on Stewart et al. (1993). The notation is as follows.

$\theta$  = angle subtended by an object coming directly towards the viewer at speed  $v$  ( $\theta$  is measured in radians, and so as it is small, it equals the ratio of the linear size of the object  $b$  to its distance  $x$ );

$\theta'$  = the rate of change of  $\theta$ ;

$\theta''$  = the rate of change of  $\theta'$ ;

$\tau = x/v$ , the time to collision if speed remains  $v$  (i.e., there is no acceleration);

$t$  = the time to collision if acceleration is  $a$ .

Starting from  $\theta = b/x$ , differentiate in order to obtain relationships between  $\theta$ ,  $\theta'$ ,  $\theta''$ , and either  $\tau$  or  $t$ .

- $\theta' = (b/x^2).v$  ( $\theta'$  and  $v$  are understood to be positive, so  $v = -x'$ )
- $\theta'' = (b/x^2).a + 2.b.v^2/x^3$

Consider use of those results if  $a = 0$ .

- $\tau$  is  $x/v$ , and one estimate of this is the ratio  $\theta / \theta'$ .
- The use of  $x/v$  as an estimate of the time to collision is based on  $a$  being 0. If  $a = 0$ ,  $x/v = 2.\theta' / \theta''$ .

Now suppose  $a$  is not 0. How accurate is  $\theta / \theta' = x/v$  as an estimate of  $t$ ? And how accurate is  $2.\theta' / \theta'' = 2.v.x/(a.x + 2.v^2)$  as an estimate of  $t$ ?

- Think of a stream of cars all travelling at the same speed. Suppose one starts to brake quite sharply, at 4 m/sec/sec. After 2 seconds, its speed relative to the following vehicle is 8 m/sec.
- For a numerical example, suppose  $x = 32$  m,  $v = 8$  m/sec,  $a = 4$  m/sec/sec.
- The time  $t$  to move 32 m is approximately 2.5 sec.
- The estimate  $x/v$  is 4 sec, fairly inaccurate and in the optimistic or unsafe direction.
- The estimate  $2.v.x/(a.x + 2.v^2)$  is 2 sec, which is more accurate and in the pessimistic or safe direction.

According to Stewart et al., "when drivers of road vehicles are in potential collision with pedestrians, their perception of distance is based primarily on familiar size, resulting in overestimation of size and therefore of time-to-collision with child pedestrians".

## ***11.6 Weaknesses of model [A] and similar theories***

Model [A] might be wrong. In response, some alternatives have been mentioned (as in section 8.5), and will be considered further in chapter 12.

Some aspects of the operation of AEB are outside the scope of the foregoing chapters. These include the following.

- The sensory aspects of an AEB system, such as how it responds in different environmental conditions and to different complexities of scene.
- Complex algorithms for distinguishing what is a positive (emergency) requiring response and what is a negative requiring no action, and their accuracy in terms of the frequencies of false negatives and false positives.
- Prediction of the position of an obstacle (such as a pedestrian) a second or two into the future.
- The reaction of the AEB system when there is plenty of time to spare (as there may be at slow speeds).

I think it unlikely, but it is imaginable that a driver might drive less safely in a car equipped with AEB or other safety technology. Maladaptation to safety measures is one of the theoretical issues briefly considered in chapter 23, see section 23.3.

Another possible secondary effect of new technologies potentially might occur in the case of cooperative or mutual assistance technologies with which one driver advises another about danger. For example, X might see danger to Y that cannot be seen by Y. Obviously there are safety benefits from communication from X to Y. Kurihashi et al. (2015) argue that there is potentially a second type of benefit: active participation by X, rather than operation of automatic communication, may improve the safety attitudes of X.

Model [A] could be criticised for not being something that it indeed is not. It does not deal with (for example) the driver's decision to travel, the driver's choice of speed  $v$ , or the decisions made by the obstacle that made it an obstacle.

### ***11.7 Testing if operation of AEB is complicated and differs between cars***

For most of this book, it is assumed that operation of AEB is fairly simple, and that it is quite similar for all cars. If that is not true, how might a testing regime operate?

A similar question will be asked in section 21.3.3, about impact testing: how might a testing regime operate if the outcome of testing has a complicated dependence on impact speed, and this is different for each impact point?

Adapted to AEB testing, the answer tentatively suggested there is as follows.

- The testing authority would require the vehicle manufacturer to estimate the performance for many different combinations of conditions ( $v$ ,  $x$ , and so on).
- The testing authority would take a random sample of combinations of conditions and in each case carry out a real physical test, as a check on the estimates provided by the manufacturer.

## 12. How to construct your own model for a driver or a vehicle acting autonomously

### 12.1 Introduction

I imagine that many readers have noticed the simplicity of model [A], 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.) 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.

The correctness of many of the specifics in chapters 6 - 11 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.

### 12.2 General style of modelling

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, analogous to  $d$  and  $t$  (or  $t + L$ ) in model [A].
- Input variables describing the conditions of the crash or the test, such as  $x$  and  $v$ .
- Desired output variables, such as the time from challenge until the AEB system commands emergency braking, distance available for braking, and impact speed. Whether or not an impact occurred is a simple output (see section 8.5.2).
- 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 Part D of this book.

### ***12.3 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 sections 5.2 and 8.1, 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 sections 5.2 and 8.1.2 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.

## ***12.4 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.
- 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.

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

- Weak braking, as discussed in section 11.3.
- "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.
- The models have referred to an obstacle clearly in the vehicle's path. This was intended to mean 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.

## 13. The effect of travelling speed on impact speed: Quantitative demonstration

### 13.1 Travelling speed and impact speed

To complete Part B of this book, this chapter considers what the effect of travelling speed on probability of death might be.

- As described in section 3.3, Joksch (1993) summarised the effect of impact speed on probability of death by a power function. That is also done in section 3.4.
- We also need to know the effect of travelling speed on impact speed. For consistency with other relationships (chapter 3), it will be approximated by a power function.

In section 8.4, the following equation was given for the square of impact speed.

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

This is a step towards numerically calculating what percentage reduction in  $u$  will result from a 1 per cent reduction in travelling speed  $v$ . This will depend on two quantities that describe how difficult the task of speed reduction is ( $v$  and  $x$ ), and on three quantities that describe the ability of the vehicle to perform the task ( $d$ ,  $t$ , and  $a$ ). We simply calculate  $u$  for travelling speed  $v$ , and for travelling speed equal to 99 per cent of  $v$ .

The total set of results will be made up of three parts.

- *The task is easy relative to the ability of the vehicle.* By this, I mean that at travelling speed  $v$ , the vehicle stops before the impact, and  $u = 0$ .
- *The task is difficult relative to the ability of the vehicle.* By this, I mean that at the lower travelling speed (99 per cent of  $v$ ), the vehicle does not commence braking before impact, and  $u = 99$  per cent of  $v$ . Therefore there was no braking at the higher speed, either.
- *Intermediate cases.* At speed  $v$ , braking commences, but the vehicle does not stop before impact. (Impact speeds for the two travelling speeds are not obvious, and need to be calculated.)

The previous paragraph splits up the results according to the speed reduction from action or inaction by the driver or vehicle. The focus of the present chapter is different, the effect of travelling speed on impact speed. That is, this chapter is not about how effective a driver or an AEB system might be in reacting. Instead, it is about what that might imply about the strength of the effect of travelling speed.

- If the task is easy,  $u = 0$  at both speeds. A 1 per cent reduction in  $v$  gives no reduction in  $u$ .
- If the task is difficult,  $u = v$  at both speeds. A 1 per cent reduction in  $v$  gives a 1 per cent reduction in  $u$ .
- The intermediate cases require calculations to be carried out.

Suppose we choose sets of values of  $v$ ,  $x$ ,  $d$ ,  $t$ , and  $a$ , and calculate the percentage reduction in  $u$  that results from a 1 per cent reduction in  $v$ . Once the calculations have been carried out, it is likely to be appropriate to limit them in two ways.

- Very low impact speeds  $u$  may be excluded, because death is very unlikely (and if it occurs, it may be for some unusual reason).
- High travelling speeds  $v$  may be excluded on the grounds that it is unreasonable to expect AEB to operate successfully at those speeds.
- Excluding low impact speeds means that cases in which there was not an impact, and therefore a 1 per cent reduction in  $v$  gives no reduction in  $u$ , are excluded.

### ***13.2 Choice of $v$ , $x$ , $d$ , $t$ , and $a$ , and choice of limitations***

The equation in section 8.4 was used to calculate  $u$ .

- There were 8 choices of  $v$ : 30, 40, 50, 60, 70, 80, 90, 100 km/h (of course these were converted to m/sec).
- There were 4 choices of  $x$ : 10, 30, 50, 70 m.
- There were 4 choices of  $d$ : 5, 10, 20, 50 m
- There were 4 choices of  $t$ : 0.0, 0.5, 1.0, 2.0 sec.
- There were 4 choices of  $a$ : 6, 7, 8, 9 m/sec/sec.

Thus at this stage, there are  $8 \times 4 \times 4 \times 4 \times 4 = 2048$  cases, or combinations of values.

Limitations on  $u$  and  $v$ .

- $u$  was limited to at least 7 m/sec (25.2 km/h), or to at least 10 m/sec (36 km/h).
- $v$  was either limited to at most 20 m/sec (72 km/h), or not limited except by the choices in the above list (the highest  $v$  was 100 km/h, which is 27.8 m/sec).

### **13.3 Results**

I acknowledge that different people will hold different opinions on what are the most appealing and enlightening choices of  $v$ ,  $x$ ,  $d$ ,  $t$ , and  $a$ , and whether there should be any further limitations on  $u$  and  $v$ .

Table 13.1 summarises the results. What the first line (for example) means is the following.

The results refer to the combinations of  $v$ ,  $x$ ,  $d$ ,  $t$ , and  $a$  that have been specified, omitting ones for which impact speed was low. For 61 per cent, impact speed reduction was only 1 per cent (because impact speed was the same as travelling speed); the other 39 per cent had an average impact speed reduction of 2.1 per cent; taking both groups into consideration, the average impact speed reduction was 1.4 per cent.

That is, when AEB is sufficiently clever that there is some braking, but the task is so difficult that impact nevertheless occurs, the magnifying factor is about 2. (By the magnifying factor, I mean the factor that multiplies the percentage travelling speed reduction to get the percentage impact speed reduction.) Of course, section 13.1 showed that the multiplying factor is 1 if AEB is useless or absent (and is 0 if the task is very easy, but these cases have been excluded).

As has already been said, different people will hold different opinions about what are enlightening or realistic values of the five quantities. Thus the numerical results (Table 13.1) are fairly tentative.

But it is feasible for anyone to calculate percentage reduction in impact speed for any set of  $v$ ,  $x$ ,  $d$ ,  $t$ , and  $a$  that they are interested in. This chapter has contributed suggestions about method. (a) The wording of the question focusses attention on getting a percentage reduction output from a percentage reduction input. (b) Model [A] is understandable. (c) Model [A] has five parameters (two for task difficulty, and three for vehicle ability). (d) The equation derived from model [A] is quite simple. (e) The organisation of the results takes into account the three levels of task difficulty relative to vehicle ability.

Table 13.1. Summary results of the percentage reduction in impact speed  $u$  (upctred) resulting from a 1 per cent reduction in travelling speed. Columns (3) and (4) give percentages. Column (5) gives the mean percentage reduction of  $u$ , for the so-called intermediate cases for which braking commenced but the vehicle did not stop. Column (6) gives the mean percentage reduction of  $u$ , for all cases that satisfied the conditions. See text for further information.

		(3)	(4)	(5)	(6)
		upctred = 1	upctred > 1	upctred mean1	upctred mean2
u = at least 7 m/sec	v = at most 20 m/sec	61%	39%	2.1	1.4
u = at least 7 m/sec	v = at most 27.8 m/sec	61%	39%	2.1	1.4
u = at least 10 m/sec	v = at most 20 m/sec	66%	34%	1.7	1.3
u = at least 10 m/sec	v = at most 27.8 m/sec	64%	36%	1.8	1.3

### ***13.4 Strong dependence of probability of death on travelling speed***

The dependence of impact speed on travelling speed might have an exponent of about 2 (Table 13.1). The dependence of probability of death on impact speed is found empirically to have an exponent of about 2.5 (section 3.4.3). The dependence of probability of death on travelling speed will therefore have an exponent of about 5. That's a very strong dependence: a 1 per cent reduction in travelling speed will lead to a 5 per cent reduction in deaths.

If we take an exponent of 5 seriously, a 5 per cent reduction of travelling speeds would lead to deaths being reduced by 23 per cent, and a 10 per cent reduction in travelling speeds would lead to deaths being reduced by 41 per cent. (For example,  $0.95^5$  is 0.77. Thus a 5 per cent reduction of speeds leads to deaths being 77 per cent of what they were, and this is a 23 per cent reduction.)

That would be expected to apply to (roughly, of course) the many road accident deaths that are caused by blunt impact. It would not be relevant to deaths caused by (for example) crushing, drowning, falling, or fire.

This book does not focus on the practicalities of accident prevention and mitigation. Nevertheless, many drivers obey speed limits, more obey speed limits when these are supported by education and efficient enforcement, and (as previously mentioned in section 3.2) such

researchers as Smeed (1961) and Newby (1970) found long ago that speed limits lead to crash reductions.

### ***13.5 Overview of chapters 11 - 13***

Chapter 11 finishes off the main line of modelling of AEB and AEB testing: sections 11.1 and 11.2 examine data from AEB testing, and sections 11.3 - 11.7 are discussions of various further issues with AEB.

- Section 11.3 discusses weak braking as a possible action of an autonomous system.
- Section 11.4 argues that a variety of methods of testing is desirable.
- Section 11.5 summarises some theory developed in the context of human drivers.
- Section 11.6 notes the limited scope of theories in the style of model [A].
- Section 11.7 sketches how, in principle, testing might operate if operation of AEB is complicated and differs between cars.

I imagine that many readers have noticed the simplicity of model [A], 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. The purpose of chapter 12 is to list some building blocks from which better models can be constructed (Hutchinson, 2016). 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, analogous to  $d$  and  $t$  (or  $t + L$ ) in model [A].
- Input variables describing the conditions of the crash or the test, such as  $x$  and  $v$ .
- Desired output variables, such as the time from challenge until the AEB system commands emergency braking, distance available for braking, and impact speed.
- 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 effect is to test the AEB system alone or the whole vehicle including brakes and tyres.

Chapter 13 reports the results of some simple calculations of the effect of travelling speed on impact speed, using an equation based on model [A].

- In sections 3.3 and 3.4, the effect of impact speed on probability of death was approximated by a power function.
- For consistency with this, the effect of travelling speed on impact speed is approximated in chapter 13 by a power function.

- It is suggested that the dependence of impact speed on travelling speed has, on average, an exponent of about 2. The dependence of probability of death on impact speed is found empirically to have an exponent of about 2.5. If those estimates are about right, the dependence of probability of death on travelling speed will have an exponent of about 5. That is, a 1 per cent reduction in travelling speed will lead to a 5 per cent reduction in deaths.

## Part C. Impact of the human

Part C has the following chapters.

14. Movement of a car in collision.
15. Movement of a car's occupants in a crash.
16. Pedestrian impacts: Testing a car's front.
17. Types of blunt impact.
18. Effect of speed (and other variables) on HIC (and other variables).
19. Data from impact tests.

Most of Part C concerns the impact of a human (e.g., a human head) with something that deforms, such as part of a car exterior or interior. But Part C begins with chapters 14 and 15 on the movement of vehicles in collisions and the movement of vehicle occupants during a crash. The topics in chapters 14 and 15 are dealt with rather briefly. There are much fuller accounts in publications that are referred to.

What is said about AEB testing at the beginning of part B (acknowledging the work of skilled experimenters) applies to impact testing also.

## 14. Movement of a car in collision

### 14.1 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. See also 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 15, 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 15.2 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 mean topics such 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.

### 14.2 Head-on impacts

The simplest geometry of collision is sufficient for this book. (There will be some consideration of rear impacts and side impacts in sections 14.3 and 14.4.)

- 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. 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 2.

The velocity change may be determined as below. Here, it is necessary to keep a clear head about the signs of the various velocities. 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 3.4.2,  $R$  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.

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

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 18.3.3.

### **14.3 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 (section 2.2) and not of central interest for this book.
- Occupants of the struck car are protected by the seat backs.

#### **14.3.1 Blame in rear impacts**

When better information is not available, the driver of the striking vehicle is often thought to be blameworthy (failure to pay attention), 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.

This might be considered an example of the induced exposure method of estimating risk, see section 23.7 and Appendix 8.

#### **14.3.2 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 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.

#### ***14.4 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 (section 2.2) 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 is 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. A possible basis for calculation is the following.

- Conservation of momentum in any direction (e.g., the direction of travel of one of the vehicles).
- Conservation of momentum in the transverse direction to that.
- Assume that the vehicles stick together, and their post-impact velocities are the same.
- Ignore rotation of the vehicles.

I would think this method would only be considered if the impact was not a glancing one, and if rotation were not of interest. The injuries are likely to have happened before the vehicles separate. (The problem of reconstruction of pre-impact velocities is a different one, and more difficult, as vehicle movements and rotations after the impact may be important.)

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.

## 15. Movement of a car's occupants in a crash

As mentioned at the beginning of chapter 14, 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 in use.

### 15.1 *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 1.4) 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 1.1). 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.

### 15.2 *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.

Table 15.1. Numbers of single-vehicle crashes in which both the driver and the front seat passenger were injured, showing who (D or P) was the more seriously injured: three combinations of injury severities, and four types of accident. Urban refers to locations where the speed limit was 40 mile/h or less, and rural refers to locations where the speed limit was more than 40 mile/h.

	Fatal & serious		Fatal & slight		Serious & slight	
	D fatal	P fatal	D fatal	P fatal	D serious	P serious
Rural nonoverturning	114	156	32	52	923	1317
Urban nonoverturning	105	152	37	79	911	1423
Rural overturning	114	119	71	58	970	1071
Urban overturning	28	23	10	21	200	217

### ***15.3 Injury severities of unrestrained driver and passenger***

On the basis of section 15.2, it is expected that an unrestrained driver will tend to be a little less seriously injured than an unrestrained front seat passenger. Table 15.1 shows that there is a difference in this direction in the case of nonoverturning accidents. The data is from Great Britain, 1969-1972 (Hutchinson, 1986, Table 2). The great majority of car occupants did not wear seat belts at this time.

Table 15.1 is an unfamiliar type of table, so I will describe how it is read. As an example, consider rural nonoverturning crashes (the first line of data). There were 114 of these in which the driver was killed and the passenger seriously injured, and 156 of these in which the passenger was killed and the driver seriously injured.

In the case of overturning accidents, presumably the movement of both driver and passenger is complex and varies a lot between accidents, and the proximity of the steering wheel to the driver is less likely to be protective.

Table 15.1 has no comparisons involving uninjured occupants (fatal and uninjured, serious and uninjured, slight and uninjured). That is because it was not possible to distinguish between a front seat passenger being present and uninjured, and absence of a front seat passenger.

#### ***15.4 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).

### ***15.5 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.

Ask anyone to give an example of a safety device, and they are quite likely to reply with crash helmet. Some people have wished that it were fashionable for vehicle occupants to use some form of crash helmet (McLean, 1979; McLean et al., 1997; Ponte et al., 2002).

## ***15.6 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 cannot have been thinking of pedestrians' legs: the bumper itself should probably be designed with a pedestrian's leg in mind.

### ***15.7 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.

### ***15.8 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 14.2), 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. British data shows no effect (Grime and Hutchinson, 1979), but 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 4 discusses reasons why the American data may be misleading and is certainly not compelling.

### ***15.9 Overview of chapters 14 and 15, and a look forward***

Chapters 14 and 15 are respectively on what happens to vehicles in collisions and what happens to their occupants. I have been quite brief, as accounts of these subjects are available elsewhere. See, for example, the book edited by P. Prasad and J. E. Belwafa, *Vehicle Crashworthiness and Occupant Protection* (available online), especially the contributions by Mahmood and Fileta (2004) and Chou (2004).

The key point in chapter 14 is the importance of the mass ratio of the two vehicles in determining the velocity change of each vehicle.

The key point in chapter 15 is that when a car has a frontal impact with a rigid barrier, an unrestrained occupant strikes the interior of the car with relative speed only a little lower than the initial speed of the car. The interior structures crush only a few centimetres, and thus accelerations of the occupants are great. Restraint systems (seat belts, air bags) greatly extend the distance of deceleration, and thus greatly reduce the accelerations.

The main topic of chapters 16 - 19 is blunt impact of a human. The chief example is that of a pedestrian with the exterior of a car, but similar principles apply to an unrestrained car occupant striking the car interior.

Chapter 16 will describe some aspects of the testing of cars for pedestrian safety. The main idea is that the exterior of a car should be considered as a cushion to protect pedestrians from stiff structures in the engine compartment. Testing is with an instrumented headform that is projected against a number of locations on the car exterior. Accelerations are measured and are summarised by calculating a quantity called the Head Injury Criterion (HIC).

The purpose of chapter 17 is to contrast four types of blunt impact. General conclusions from chapter 16 are likely to be valid for other impacts of the same type, but not for impacts of other types. (The same will apply to the theoretical results to be obtained in chapter 18.) The four types are as follows.

- Small rigid human, impact with large deformable object. Pedestrian headform tests are examples of this type.
- Large deformable human, impact with small rigid object.
- Small deformable human, impact with large rigid object.
- Large rigid human, impact with small deformable object.

Acceleration-based measures such as HIC are only relevant when the human accelerates, i.e., is the "small" object. Deformation-based measures are only relevant when the human deforms, i.e., is the deformable object.

The starting point in chapter 18 is to assume that a specific differential equation relates the force at any instant during the impact with 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. It will be shown that maximum acceleration and HIC are proportional to power functions of initial velocity ( $v$ ) and mass ( $m$ ) of headform; expressions are obtained for the exponents in terms of the exponent ( $n$ ) applying to the nonlinear spring. For example, it is found that HIC is proportional to  $m^{-1.5/(n+1)} \cdot v^{(4n+1)/(n+1)}$

It is quite common to test things that may hit a human, or that are intended to protect the human. The analysis of data collected in such tests seems to me to be often incomplete. Chapter 19 comments on some published data. The examples are all from transport safety contexts. In discussion at the end of the chapter, it is said that extra insights into the data are often obtained by comparison with theory. But on the other hand, it seems that theory can help only a little with present-day datasets: measurement of the dependent variable is often less accurate than one might wish, there is often only one independent variable (e.g., impact speed), the independent variable often has only a limited range, and there is often only one dependent variable (e.g., HIC).

## **16. Pedestrian impacts: Testing a car's front**

### ***16.1 Introduction***

This chapter 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.) This example is important in itself, and to serve as a base from which other types of impact can be considered. Much of this chapter is based on part of Hutchinson, Searson, et al. (2011). Chapter 2 of Hutchinson (2018) is similar to this chapter. A highly relevant book is that by Simms and Wood (2009).

In recent decades, increasing attention has been paid to improving car frontal design in order to minimise pedestrian injury. The first point to make is that, 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.

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.

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. 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 18.2.2.) 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.

Several points about bonnet stiffness are worth making straightaway.

- 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.
- 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.
- But 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 sections 16.3 and 20.5.1 and the further discussion in Appendix 9.

## ***16.2 General principles of bonnet design for pedestrian safety***

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. For a review of market penetration and safety performance of such systems, see Ames and Martin (2015).

- 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. 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.

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.

These principles indicate that 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, car companies 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 conducted for consumer information purposes only. That is, 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 the present book 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.

### ***16.3 Bonnet stiffness as a special case***

In the case of bonnet stiffness, 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.
- A class of possible laws will be proposed in section 18.4; if (for example) the exponent  $n$  in that class of laws is different for different bonnets, cross over may occur.

See Appendix 9 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.

## ***16.4 Discussion***

Testing using a single test speed and headform mass will lead to improved pedestrian safety in those conditions. Several types of design change are available (see section 16.2 and Appendix 5). However, an improvement achieved by making the bonnet less stiff may worsen safety at higher speeds and higher masses because of bottoming out, and an improvement achieved by stiffening the bonnet may worsen safety at lower speeds and lower masses. Thus to achieve balance between these conflicts, estimates of safety performance at other speeds and headform masses are required. Furthermore, it will be desirable to develop methods

of calculating an average level of performance that take into account the frequency with which different speeds and head masses occur.

The desirability of obtaining results over a range of speeds does not necessarily imply that the number of tests would be drastically increased. Firstly, when clearance distances are sufficient that bottoming out does not occur, simple calculation as will be described in section 18.5 can convert the Head Injury Criterion obtained at one speed and headform mass to other test conditions. Secondly, testing could be carried out for only some of the combinations of conditions. (The combinations might be randomly chosen, as the aim would be to get a good estimate of the safety performance of the vehicle, rather than to gain new knowledge about some location of impact on it.)

In general terms, there is a steep increase of severity with speed of striking a stiff structure beneath the bonnet. Thus the chief penalty for failing to take account of the range of real-world speeds and head masses is likely to be at high speeds and high masses. However, this is poorly understood quantitatively, and both experiment and modelling are needed to improve knowledge of what designs and materials are optimal.

The principles given here 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).

## 17. Types of blunt impact

### 17.1 *Introduction*

The purpose of this chapter is to contrast the pedestrian headform tests described in chapter 16 with other tests that are, or might be, carried out to test some other manufactured object. The headform tests will be put into the context of four simple types of test.

In designing a test, one would like to know what physical quantity is most closely responsible for injury. Possibilities include acceleration, 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. This chapter does at least serve as a warning that results that might be obtained for the pedestrian headform tests of chapter 16 (for example, in chapter 18) will not necessarily be transferable to other types of impact test. Chapter 3 of Hutchinson (2018) 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 (non-penetrating) injury is considered.
- 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.

### 17.2 *Contrasts between two objects that collide*

My opinion is that a useful way of comparing different types of impact is as follows. Consider the 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.

### ***17.3 Four types of impact***

The contrasts of mass and of deformability 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, see chapter 16.
- 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; and fruits and vegetables striking the sides and bottoms of containers and channels are likely to be analogous.
- 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. 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.

### ***17.4 Proxies for injury: Contrast between acceleration and deformation***

In each of the types of impact described in section 17.3, 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.

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 16.1. 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.

## ***17.5 Discussion***

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  $S$  or  $VC_{max}$ ) 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 18.

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 will be given in section 18.8.4 of a change in conditions giving a reduction in maximum acceleration and an increase in HIC.
- Despite the example in section 18.8.4, a change in conditions will usually change maximum acceleration and HIC in the same direction. It is much more likely that a concept based on force or on deformation will behave differently from one based on acceleration.

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.
- For fracture of bone, including the skull, many people think that maximum force is important.
- See also section 18.6 below.

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.

## 18. Effects of speed (and other variables) on HIC (and other variables)

### 18.1 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. Examples include the interior of a vehicle, the bonnet and other parts of a vehicle exterior, 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 in the sense that they reflect movement and a realistic impact. They are not static measurements of simple stiffness.

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 set of conditions is likely to imply something about what HIC would be in other conditions.

There is more on the topic of this chapter in chapters 4 - 6 of Hutchinson (2018).

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.

## ***18.2 Force, represented in a differential equation***

### **18.2.1 Introduction**

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:

$$m \cdot x'' = \text{some function of } x \text{ and } x'$$

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 outer shell of 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.

### **18.2.2 The Head Injury Criterion (HIC)**

The Head Injury Criterion HIC is  $[\text{av}(a)]^{2.5} \cdot (t_2 - t_1)$ , where  $\text{av}(a)$  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.

### 18.2.3 Outputs from a differential equation

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  $x''(t)$ .

## 18.3 *Linear and nonlinear springs*

### 18.3.1 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.

### 18.3.2 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.)

### 18.3.3 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 (2018).

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.

### 18.3.4 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,  $k \cdot x^n$  integrated from 0 to  $S$ , which equals  $k \cdot S^{n+1} \cdot (1/(n+1))$ .

- This must equal kinetic energy of impact,  $\frac{1}{2}.m.v^2$ .
- 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).

The concern here is to start from a differential equation, and obtain relationships between inputs and outputs. Observed relationships between inputs and outputs then have implications for what the differential equation may be. Alternatively, a direct approach of attempting to predict moment-to-moment force from moment-to-moment displacement and moment-to-moment velocity might be proposed. This approach is not taken in this book. Miller et al. (1996) did suggest concentrating attention on force versus displacement, rather than force or acceleration versus time.

#### ***18.4 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  $t$  passes, 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).

### 18.5 Proportionality results

It turns out that, for the above differential equation, 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  $(m/k)^{-1/(n+1)} \cdot v^{2n/(n+1)}$ .
- Duration  $T$  is proportional to  $(m/k)^{1/(n+1)} \cdot v^{-(n-1)/(n+1)}$ .

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

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

For convenience, the exponents are listed in Table 18.1.

Table 18.1. 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  $HIC \propto S^{-1.5} \cdot v^4$ .
- On the assumption of an asymmetric haversine pulse (as they call it), Zhou et al. (1998) algebraically demonstrated that  $HIC \propto S^{-1.5} \cdot v^4$ .
- 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  $HIC \propto S^{-1.5} \cdot v^4$ .

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

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

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.

## ***18.6 Other proxies for injury: Comments relevant to force and strain***

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.

In a detailed modelling context (using the finite element method), Kleiven and von Holst (2002) found a negative effect of mass on HIC and a positive effect on measures of intracranial stress. Ruan and Prasad (2006) found that for a given acceleration pulse, a head having twice the mass of another received twice the force (the differences they found for stress probably in part reflected differences in skull thickness). Mertz (1993) suggested that depending on head mass, rather different values of HIC should be considered as being equivalent as regards injury. The figures at p. 81 of Mertz (1993) imply that it is more appropriate to treat the product of HIC and  $m^{0.25}$  as a constant criterion than either HIC or the product of HIC and  $m$ . For discussion of HIC and other simple measures as compared with complex measures calculated from finite element models of the head

and brain and based on strains and stresses, see Sanchez-Molina et al. (2012).

In section 17.5 it was noted that the effects of conditions of impact are different for the different proxies for injury, and may even be in opposite directions (and there will be an example in section 18.8.4).

- At the present state of knowledge, we should regard this as a warning to think carefully about any use of physical measures supposedly reflecting injury that is different from the limited circumstances intended.
- Testing and the calculation of HIC are carried out according to a tightly-specified procedure, for a particular purpose. The purpose may not be exactly the same in regulatory tests as for consumer-information tests, and may even be viewed slightly differently by different parties to the tests; nevertheless, the core is a comparison of a vehicle with a standard and with other vehicles.
- In view of that narrow context, it should not be surprising if difficulties are encountered in attempting to give a broader meaning to an observed value of HIC. (I do consider this a worthwhile aim, as I made clear in section 18.1.)

## ***18.7 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  $\frac{1}{2} \cdot m \cdot v^2 = \frac{1}{2} \cdot m \cdot v_e^2 + E$ . (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 18.8.

As far as I know, the empirical evidence supporting the model considered in section 18.4 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 18.4 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, 2018, especially sections 5.4.3, 6.7.4, and 12.4.)

## ***18.8 Are HIC and maximum acceleration similar concepts?***

The relationships obtained above throw some light on the question of whether HIC and maximum acceleration  $A_{\max}$  --- which are both intended to reflect the likely severity of injury --- 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, the relationships obtained in section 18.5 imply that 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  $k$ ?

At this point, let us rephrase the question of whether HIC and  $A_{\max}$  are more or less equivalent, in several ways.

### **18.8.1 Co-variation due to variation in speed**

Are HIC and  $A_{\max}$  sufficiently closely linked that, if we are referring to a particular impact point on a particular vehicle (this refers to a particular stiffness, among other things) and a particular headform, then as speed varies, HIC and  $A_{\max}$  co-vary and it is possible to calculate one from the other?

- A proportionality relationship may be obtained.

- The relationships that hold for different impact points and different headforms are likely to be different.
- There may be something similar in the relationships that hold for different impact points and different headforms. For example, after taking logarithms, the slope may be the same.

### 18.8.2 Co-variation due to variation in headform mass

Are HIC and  $A_{\max}$  sufficiently closely linked that, if we are referring to a particular impact point on a particular vehicle and a particular speed, then as headform mass varies, HIC and  $A_{\max}$  co-vary and it is possible to calculate one from the other?

- A proportionality relationship may be obtained.
- The relationships that hold for different impact points and different speeds are likely to be different.
- There may be something similar in the relationships that hold for different impact points and different speeds. For example, after taking logarithms, the slope may be the same.

### 18.8.3 Co-variation due to variation in stiffness

Are HIC and  $A_{\max}$  sufficiently closely linked that, if we are referring to a particular speed and a particular headform, then as impact point (and thus presumably stiffness) varies, HIC and  $A_{\max}$  co-vary and it is possible to calculate one from the other?

- A proportionality relationship may be obtained.
- The relationships that hold for different speeds and different headforms are likely to be different.
- There may be something similar in the relationships that hold for different speeds and different headforms. For example, after taking logarithms, the slope may be the same.

### 18.8.4 Co-variation due to variation in two factors

Consider now a particular impact point on a particular vehicle (for example), and variation in both speed and headform mass. Are HIC and  $A_{\max}$  sufficiently closely linked that as speed and headform mass vary, HIC and  $A_{\max}$  co-vary and it is possible to calculate one from the other?

Now the answer is no. One pair of conditions may have the higher HIC and the other have the higher  $A_{\max}$ .

As a numerical example, suppose that  $n = 1$ , and that therefore the exponents of  $m$  are  $-0.5$  (for  $A_{\max}$ ) and  $-0.75$  (for HIC), and the exponents of

$v$  are 1 (for  $A_{\max}$ ) and 2.5 (for HIC). Suppose  $m$  is multiplied by 2 and  $v$  is multiplied by 1.27. The effect on  $A_{\max}$  is to multiply it by  $2^{-0.5} \cdot 1.27$ , and the effect on HIC is to multiply it by  $2^{-0.75} \cdot 1.27^{2.5}$ . That is, the effect on  $A_{\max}$  is to reduce it by 10 per cent, and the effect on HIC is to increase it by 8 per cent.

### 18.8.5 Proportionality relationships

Suppose that, as predicted in section 18.5,  $A_{\max}$  is proportional to  $(m/k)^{-1/(n+1)} \cdot v^{2n/(n+1)}$  and HIC is proportional to  $(m/k)^{-1.5/(n+1)} \cdot v^{(4n+1)/(n+1)}$ . HIC is thus proportional to  $A_{\max}^{1.5} \cdot v$ , irrespective of  $m$  and  $k$ .

If  $m$  and  $k$  are constant and  $v$  is varying,  $\text{HIC}^{2n/(4n+1)}$  is proportional to  $v^{2n/(n+1)}$ , and therefore  $\text{HIC}^{2n/(4n+1)}$  is proportional to  $A_{\max}$ . Thus HIC and  $A_{\max}$  are connected by a power relationship, but the exponent is not known. It might be thought that  $n$  is approximately 1. Then  $\text{HIC}^{0.4}$  would be proportional to  $A_{\max}$ . That is, HIC would be proportional to  $A_{\max}^{2.5}$ .

Similarly, if  $k$  and  $v$  are constant and  $m$  is varying,  $\text{HIC}^{2/3}$  is proportional to  $A_{\max}$  (that is, HIC is proportional to  $A_{\max}^{1.5}$ ). Thus HIC and  $A_{\max}$  are connected by a power relationship, and the exponent is known (and does not depend on  $n$ ).

And if  $m$  and  $v$  are constant and  $k$  is varying,  $\text{HIC}^{2/3}$  is proportional to  $A_{\max}$  (that is, HIC is proportional to  $A_{\max}^{1.5}$ ). Thus HIC and  $A_{\max}$  are connected by a power relationship, and the exponent is known (and does not depend on  $n$ ).

In short, the relationship between HIC and  $A_{\max}$  will depend on what it is that is responsible for the co-variation between them. In a study of motorcycle helmet drop-test performance, Zellmer (1993) considered the possibilities that HIC is proportional to  $A_{\max}^{2.5}$ , or (alternatively) HIC is proportional to  $A_{\max}^{1.5}$ . He did not quite appreciate that either might occur, depending on what the source of the co-variation is.

For many years, some people have thought that when  $v$  changes, HIC is proportional to  $A_{\max}^{2.5}$ . They are correct, if  $n$  is 1.

- It is not clear exactly what people have thought, or on what grounds. The belief has probably arisen from algebra that shows this to be the case in some special cases of pulse shape, provided pulse shape does not change when  $v$  changes (Chou and Nyquist, 1974), and appreciation that pulse duration does not change in the case of the linear spring.
- HIC is proportional to  $A_{\max}^{(4n+1)/(2n)}$ , and the exponent must be greater than 2, as  $n$  is positive. This is more flexible than the idea that  $\text{HIC} \propto A_{\max}^{2.5}$ , which has some history behind it.

## 19. Data from impact tests

### 19.1 *Consequences of a theoretical model*

I am interested in data, and seeing what theoretical ideas it tends to support and what it tends to refute. Looking at data is also a good method of generating ideas.

It is quite common to test things that may hit a human, or that are intended to protect the human. The analysis of data collected in such tests seems to me to be often incomplete. In this chapter I will comment on some published data. The examples will all be from transport safety contexts. Chapter 7 of Hutchinson (2018) is similar to this chapter, and there are examples of analysis of impact data from other areas of application (e.g., sports, children's play, military contexts) in chapters 8 - 14 of Hutchinson (2018). There are even some further examples in Hutchinson (2018) relevant to transport safety: concerning aircraft seating (sections 11.5 and 11.6), impact with a vehicle interior (section 12.2), the Viscous Criterion (sections 13.4 - 13.6), and impacts of headforms or bicycle helmets with rigid surfaces (sections 14.2 - 14.4).

I should emphasise that I do not intend to criticise the authors whose work I discuss.

- On the contrary, it is praiseworthy that they have published their work with sufficient clarity that it can be fruitfully discussed.
- Impact experimentation is difficult. I am not a practical experimenter, and I hope I usually sympathise regarding the problems faced.
- There has not been much theory available for their guidance.

On the basis of section 18.5, it is worthwhile investigating whether the relationship between each of several independent (input) variables and each of several dependent (output) variables is a power function.

- Input variables: speed of impact, mass of headform, surface impacted.
- Output variables: maximum deformation, maximum acceleration, HIC. (Duration of impact is not often analysed. Also, if  $n$  is close to 1, duration will be almost independent of impact speed, and it is likely to be difficult to conclude whether there is any dependence.)
- And the exponents in the relationships should all be consistent with some particular value of  $n$ .

Concerning surface impacted, there is usually no quantitative measure available (e.g., stiffness). Instead, it might simply be recorded as impact point 1, 2, 3, etc. Thus analysis will need to be of the co-variation of output

(dependent) variables, rather than of the dependence of output variables on stiffness --- see section 19.3 especially.

## ***19.2 Empirical studies***

Blunt injury is important in many contexts --- transport, at work, at home, playing sports, children's play, military conflict, and so on. Blunt damage (especially to manufactured objects, and to agricultural produce) is important also.

There is therefore quite a lot of relevant experimentation. Some impressions I have of the literature (including experiments conducted outside of the road accident context) are as follows.

- Data analysis is usually much more limited than what is suggested in section 19.1.
  - Relationships are usually in the expected directions.
  - Relationships are usually compatible with power functions.
- However, the consistency of the experimentation and the accuracy of measurement are often not good enough to say whether relationships are power functions or whether some other function is a better description.

I have also seen other papers in which the results are complicated and puzzling, when viewed in the light of the predictions in Hutchinson (2013) and chapter 18 above. It might be said that such papers constitute evidence that the predictions are poor ones. But I am not convinced of that. It seems more likely to me that something went wrong (and there are generally so few experiments that even one false result is likely to obscure the whole pattern), or that some phenomenon occurred that is outside the scope of the theory (e.g., bottoming out).

You might ask, what can a reader expect from this chapter?

- A few people will be seriously interested in the examples discussed. They will read the paper referred to, understand the experiment and the data presented, and evaluate the suggestions and comments that I make.
- But I am not expecting that most people will be so deeply interested. Most will not read the paper referred to. So I am intending that you will get value simply from the brief account that I give. You will gain an idea of what questions are studied, the types of experiment performed, the amount and nature of the data collected, and the associated limitations. You will be able to appreciate that the experiments are usually quite narrowly focused, with little concern for theory or for experimental conditions other than those actually used.

- The comments that I make about the experimental results are usually quite simple ones, and I have not supported them with graphs and scatterplots and complicated statistics.

My reaction to the examples in sections 19.4 - 19.14, and I expect many readers will share it, is that extra insights into a dataset can be obtained by comparing it with theory, but these insights are rather limited, and it seems that theory can help only a little with present-day datasets.

### ***19.3 How pairs of dependent variables co-vary***

#### **19.3.1 HIC and maximum acceleration**

In addition to relationships between the independent variables and the dependent variables, the way that two dependent variables co-vary may be of interest. This is especially the case for maximum acceleration and HIC, as both these are used to reflect injury. And either of these might be plotted versus maximum displacement, also.

There may be particular reasons for plotting one dependent variable versus another.

- An independent variable might be absent. For example, there might be a categorical variable identifying impact location, but no quantitative variable giving the surface stiffness.
- There may be some question about the accuracy of measurement of an independent variable.
- An independent variable might not be appropriate in the context of some credible theory of interest. For example, possible use of an effective impact speed rather than actual impact speed was mentioned in section 18.7.

Proportionality relationships between HIC and maximum acceleration were given in section 18.8.5. The relationship is different according to which variable is responsible for the co-variation, and which variables are constant.

#### **19.3.2 Maximum deformation and a proxy for injury severity**

Now consider the correlation between a proxy for severity of injury to the head (such as HIC or maximum acceleration) and a measure of amount of damage to the vehicle (such as maximum deformation). This will provide another example of considering the source of (that is, the reason for) the correlation.

*Impacts with a particular surface at different speeds.* Here, speed is the reason for the correlation. For a given surface, increasing speed will mean

increasing HIC (i.e., increasing severity of injury) and increasing maximum deformation (i.e., increasing damage to the vehicle). There will be positive correlation between the two output variables.

*Impacts with various surfaces at a particular speed.* Here, the variation in the surface is the reason for the correlation. The simplest type of variation in an impacted surface is in respect of its stiffness. For a given speed, increasing stiffness will mean increasing HIC (i.e., increasing severity of injury) and decreasing maximum deformation (i.e., decreasing damage to the vehicle). There will be negative correlation between the two output variables.

This example is dramatic because changing the source of the correlation changes the co-variation from positive to negative. In the case of co-variation of HIC and maximum acceleration as discussed in section 18.8.5, the relationship changed quantitatively, but remained positive.

#### **19.4 Example 1: Searson et al. (2012)**

Searson et al. (2012) reported on 29 headform impact tests at several speeds on the exterior of passenger vehicles.

- Impacts were made at seven locations on vehicles. These were on three different models of vehicle.
- At least three speeds of impact were used at each location. The lowest speed was approximately 75 per cent of the highest.
- Both HIC and maximum deformation were reported.

Searson et al. gave some theory for the dependence of HIC on impact speed and the dependence of maximum deformation on impact speed. The theory was based on assuming the impact was with a linear spring. On that assumption, they found the two dependences would be power functions with slopes of 2.5 and 1.0. Thus the relationships were expected to be linear on logarithmic axes, with slopes of approximately 2.5 for HIC and 1.0 for maximum deformation.

Findings may be summarised as follows.

- Observed relationships were approximately straight lines after logarithmic transformation: this means that the dependence of HIC on impact speed and the dependence of maximum deformation on impact speed are approximately power functions.
- Those conclusions can only be tentative. A stronger conclusion is impossible because only a few speeds were used at each location, and only a narrow range of speeds was used at each location. The data is compatible with other functional forms as well as with power functions.
- For HIC, the slopes were between 1.61 and 3.04 for the seven locations, averaging about 2.5.

- For maximum deformation, the slopes were between 0.65 and 1.33 for the seven locations, averaging about 0.8.
- There was a negative correlation between the two slopes. (The location having the highest slope for dependence of HIC on speed had the lowest slope for dependence of maximum deformation on speed, and vice versa.)

The theory of section 18.4 has the linear spring as a special case, but is more general.

- A slope other than 2.5 for HIC and other than 1.0 for maximum deformation is interpreted as the exponent  $n$  in the differential equation (section 18.4) being different from 1.
- From section 18.5, the two slopes will be  $(4.n + 1)/(n + 1)$  for HIC and  $2/(n + 1)$  for  $S$ . Let these be  $\text{slopeH}$  and  $\text{slopeS}$ . Eliminating  $n$ ,  $\text{slopeH}$  is predicted to be  $(8 - 3.\text{slopeS})/(3 - \text{slopeS})$ . For  $\text{slopeS}$  being between 0.6 and 1.4,  $\text{slopeH}$  would be predicted to be between 2.58 and 2.37.
- Thus a negative relationship between the two slopes is predicted.
- However, the predicted relationship is rather different from that found. The empirical result was that as  $\text{slopeS}$  changed from 0.65 to 1.33,  $\text{slopeH}$  changed from 3.04 to 1.61.
- The wide range of slopes --- implying a wide range of  $n$  --- is itself to some extent a point against the theory. There were similar impacts on similar objects: one might expect the slopes to be similar.
- Searson et al. said that there was no bottoming out in their tests. Nevertheless, it may be pointed out that bottoming out in the impact at the highest speed would imply low  $S$  and high HIC, and thus low  $\text{slopeS}$  and high  $\text{slopeH}$ .

### ***19.5 Example 2: Mizuno and Kajzer (2000)***

The source of the data is Figure 23 of Mizuno and Kajzer (2000) (also, Figure 9 of Mizuno et al., 2001). That Figure plots HIC at three impact speeds, for one location on a bonnet and one location on a windscreen.

The data may be summarised as follows. (All figures are approximate.)

- Bonnet. When impact speed changes by a factor of 1.67, HIC changes by a factor of 3.24. The exponent for the dependence of HIC on speed is therefore 2.30. This corresponds to  $n$  being about 0.8.
- Windscreen. When impact speed changes by a factor of 1.67, HIC changes by a factor of 6.03. The exponent for the dependence of HIC on speed is therefore 3.52. This corresponds to  $n$  being about 5.0.

Mizuno and Kajzer did not interpret the two relationships as power functions, but referred to them as linear. (HIC would be zero when speed is zero. A power function predicts this correctly, but a straight line does not.)

Pereira (2010) reports HIC at eight bonnet locations, each at two speeds (35 km/h and 40 km/h). A child headform was used at five locations, and an adult headform at three. The factors by which HIC increased at the higher speed imply exponents of between 1.3 and 3.0 for the dependence of HIC on  $v$  (if dependence is assumed to be a power function). These fall within the range of 1 to 4 that is implied by the relationships of section 18.5.

For another aspect of the work of Mizuno and Kajzer (2000) (also, Mizuno et al., 2001), see section 19.7.

There is a little data on both  $A_{\max}$  and HIC versus impact speed in Mizuno et al. (2017). It refers to A-pillar impacts of helmeted pedal cyclists.

### **19.6 Example 3: Anderson et al. (2000)**

Anderson et al. (2000) reported on tests in which a headform was dropped on to a specimen of a material under test, that was supported on a steel slab. The context of this work was the development of a protective headband intended for wearing by car occupants. Results for impacts at 16.0 km/h and 19.2 km/h with five materials are given. The five materials were referred to as: CF-45100 at a temperature of 15-17 degrees, BB-38 at 25-26 degrees, E175 at 25-26 degrees, E900\_5.6 at 25-26 degrees, and E900\_6.0 at 25-26 degrees.

It is convenient to give the relevant theoretical results first, and then examine the empirical findings. The higher speed of impact is 1.20 multiplied by the lower speed. For the Hunt and Crossley (1975) model, section 18.5 gave some theoretical results.

- The exponent for maximum acceleration is  $2.n/(n + 1)$ , which cannot exceed 2. Thus the ratio of maximum acceleration for the two speeds cannot exceed  $1.2^2 = 1.44$ .
- The exponent for HIC is  $(4.c + 1)/(c + 1)$ , which cannot exceed 4. Thus the ratio of HIC for the two speeds cannot exceed  $1.2^4 = 2.07$ .

The findings in Anderson et al. (2000) were as follows.

- For maximum acceleration, the prediction was disconfirmed for all five materials. The median ratio of maximum acceleration at the two speeds was 1.68.
- For HIC, the prediction was disconfirmed for four of the five materials. The median ratio of HIC at the two speeds was 2.52.

That is, the effects of speed on maximum acceleration and HIC are greater than is possible with the Hunt and Crossley model.

A possible reason for inapplicability of this model is bottoming out. For CF-45100 at 15-17 degrees, this is discussed by Anderson et al. (p. 14 of their report).

### ***19.7 Example 4: HIC and maximum deformation***

The situation considered here and in section 19.8 is that the object impacted, or the impact location on one object, is changing, and speed is not. Such data may be quite common. Many impact tests that are reported are all conducted according to the same protocol: conditions are identical, including impact speed, but the impacts are on different objects.

HIC is proportional to  $S^{-1.5}$  if impact speed,  $b$ , and  $n$  are constant (see section 18.5).

Relevant results include the following.

- Figure 24 of MacLaughlin and Kessler (1990) (also, Figure 7 of NHTSA, 1993) shows a strong negative relationship between HIC and  $S$ , for approximately 14 impact tests on the bonnets of each of 12 vehicles. The impacts were at 23 mile/h, normal to the surface. A power curve fit is shown,  $HIC \propto S^{-2.1}$ . MacLaughlin and Kessler note that several of the high values of HIC probably occurred because of contact with the suspension system tower; such bottoming out would be expected to distort the relationship given in section 18.5.
- Figure 25 of Mizuno and Kajzer (2000) shows strong negative relationships between HIC and  $S$ , for a set of tests on the bonnet top and a set of tests on the windscreen of a car. The impact speed was 40 km/h. Power curves are shown, with exponents of -2.1 (bonnet) and -1.8 (windscreen). Another account is in Mizuno et al. (2001).
- Figure 13 of Han and Lee (2003) shows a strong negative relationship between HIC and  $S$ , for 13 impact tests on the bonnet of a production car and one modified for greater pedestrian safety. The impacts were at 40 km/h, with a 2.5 kg headform.

For the data of Han and Lee (2003), I have plotted  $\ln(HIC)$  vs.  $\ln(S)$ .

- The relationship is a good straight line.
- The relationship appears to be the same for the modified car as for the production car.
- The slope is about -2.2.

Naturally, the data points differ in respect of location on the car bonnet. If locations differed only in respect of stiffness (and the Hunt and Crossley model of chapter 18 were valid), the slope would be -1.5. But it is likely the headform was projected at a specific angle to the horizontal, and as the bonnet is at different angles to the horizontal at different locations, the component of velocity normal to the bonnet surface would be different at different locations. This might account for the relationship being rather different from that expected.

Masoumi et al. (2011) conducted finite element modelling of pedestrian headform impacts with bonnets. Both HIC and S are reported for 8 locations on 3 bonnets (steel standard design, aluminium standard design, and composite simplified design). I have plotted  $\ln(\text{HIC})$  vs.  $\ln(\text{S})$  for the three bonnets.

- The relationship is a good straight line. The slope is estimated to be about -1.1. (This is not significantly different from -1.5.)
- Some choices made in obtaining that result should be noted. The modelling included some adult headform impacts and some child headform impacts. The headforms differed in respect of mass, diameter, and angle at which they were projected, but I did not disaggregate the analysis. In the case of four impacts, S (but not HIC) is given as exactly the same. I have included the first of these, as the acceleration-displacement curve (Figure 11 of Masoumi et al.) confirms the result, but excluded the others.

### ***19.8 Example 5: Miller et al. (1996)***

Section 18.8.5 considered what the relationship between HIC and  $A_{\max}$  would be if variation in stiffness  $k$  were responsible for their co-variation. HIC would be proportional to  $A_{\max}^{1.5}$ .

Miller et al. (1996) plotted HIC(d) (a modified version of HIC) versus  $A_{\max}$  for approximately 400 Free Motion Headform (FMH) impacts with vehicle interiors, the impact speed being 15 mile/h (perpendicular to the surface). Their Figure 4 shows a strong positive correlation between HIC(d) and  $A_{\max}$ . Miller et al. had no theory for the relationship, and they fitted an empirical quadratic equation to the dependence of HIC(d) on  $A_{\max}$ . The scatterplot can be seen to be concave upwards, and this is confirmed by the coefficient of the term in  $A_{\max}^2$  being positive.

The original HIC can readily be calculated from any given HIC(d). Looking at Figure 4 of Miller et al., at  $A_{\max} = 100$ , HIC(d) is seen to be approximately 500, and this implies  $\text{HIC} = 442$ ; at  $A_{\max} = 300$ , HIC(d) is approximately 2000, and this implies  $\text{HIC} = 2430$ .

Thus multiplying  $A_{\max}$  by 3 corresponds to multiplying HIC by 5.5 (=  $2430/442$ ). Consequently, HIC is approximately proportional to  $A_{\max}^{1.55}$  (as  $3^{1.55}$  is 5.5). This is close to the predicted relationship that HIC is proportional to  $A_{\max}^{1.5}$ .

## **19.9 Example 6: Oikawa et al. (2016)**

Oikawa et al. (2016) report both maximum acceleration and HIC for impacts of a headform, either wearing or not wearing a bicycle helmet, with the A-pillar of a vehicle. They also report both maximum acceleration and HIC for impacts of a headform, either wearing or not wearing a bicycle helmet, with the road pavement. This data is interesting particularly because the values of HIC were high: over 2000 in the A-pillar impact of a headform with helmet, and over 800 in the road surface impact of a headform with helmet. For the A-pillar impact, the impact speed was 35 km/h (but this was not at 90 degrees to the A pillar). For the road surface impact, the drop height was 1.5 m, and the speed was thus approximately 20 km/h.

If the effect of a helmet is to change the stiffness parameter  $k$  in the Hunt and Crossley (1975) equation, HIC would be proportional to  $A^{1.5}$  (see section 18.8.5).

- For the A-pillar impact, the empirical results of Oikawa et al. imply an exponent of 1.48.
- For the road surface impact, the empirical results imply an exponent of 1.42.

As already mentioned in section 19.5, there is a little data on both  $A_{\max}$  and HIC versus impact speed in Mizuno et al. (2017). It refers to A-pillar impacts of pedal cyclists.

Ito et al. (2014) report a finite element simulation of a cyclist's impact with an A pillar at 41.8 km/h. A bicycle helmet did reduce HIC and  $A_{\max}$ , but by only 21 per cent and 6 per cent respectively. Ito et al. note that substantial bottoming out of the helmet liner occurred. The percentage changes are in the ratio 3.5, not 1.5; thus in this case, wearing a helmet seems to be not equivalent to a change of stiffness. Mizuno et al. (2017) also report a finite element simulation.

## **19.10 Example 7: Monk and Sullivan (1986)**

### **19.10.1 Introduction**

Monk and Sullivan (1986) were concerned with padding a vehicle's A pillar to mitigate the impact of an occupant of the vehicle. They were aware that Chou and Nyquist (1974) had established that  $HIC = 0.0296 \cdot \Delta V \cdot A_{\max}^{1.5}$  for a half sine acceleration pulse. Monk and Sullivan felt that velocity change  $\Delta V$  was probably close to impact speed  $v$  in the tests they considered. These were of 1 inch thick padding, impact speeds being between 5 mile/h and 20 mile/h. Monk and Sullivan found

that values of HIC predicted on that basis were within 15 per cent of those observed. The tests used a Hybrid III headform.

### 19.10.2 Effects of impact speed

Concerning the effect of impact speed, I have fitted three equations to data in Table 5 of Monk and Sullivan. In each case, a constant effect of padding material was also estimated. Thus in each case the slope represents an average over all materials.

- In a regression of  $\ln(S)$  in terms of  $\ln(v)$ , a coefficient of 0.68 was found. This implies that exponent  $n$  is about 1.9.
- In a regression of  $\ln(A_{\max})$  in terms of  $\ln(v)$ , a coefficient of 1.56 was found. This implies that exponent  $n$  is about 3.6.
- In a regression of  $\ln(\text{HIC})$  in terms of  $\ln(v)$ , a coefficient of 3.33 was found. This implies that exponent  $n$  is about 3.5. (Kessler and Monk, 1989, mentioned an empirical relationship in which HIC was proportional to  $v^{2.93}$ .)

### 19.10.3 Relationships that may apply to data for all materials

In addition, there are relationships that might apply to data for all materials, provided the materials differ only in stiffness  $k$  (and not in damping constant  $b$  or exponent  $n$ ).

Firstly, HIC should be proportional to  $A_{\max}^{1.5} \cdot v$ .

- In a regression of  $\ln(\text{HIC})$  in terms of  $\ln(A_{\max})$  and  $\ln(v)$ , coefficients of 1.6 and 0.8 were found.
- A scatterplot of  $\ln(\text{HIC})$  versus  $\ln(A_{\max}^{1.5} \cdot v)$  shows an excellent straight line.
- The slope of that straight line is estimated to be 1.0.

Secondly, HIC should be proportional to  $S^{-1.5} \cdot v^4$ .

- Regression of  $\ln(\text{HIC})$  in terms of  $\ln(S)$  and  $\ln(v)$  found coefficients of -1.8 and 4.6.
- A scatterplot of  $\ln(\text{HIC})$  versus  $\ln(S^{-1.5} \cdot v^4)$  shows an excellent straight line.
- The slope of that straight line is estimated to be 1.1.

Thirdly,  $A_{\max}$  should be proportional to  $S^{-1} \cdot v^2$ .

- Regression of  $\ln(A_{\max})$  in terms of  $\ln(S)$  and  $\ln(v)$  found coefficients of -1.1 and 2.3.
- A scatterplot of  $\ln(A_{\max})$  versus  $\ln(S^{-1} \cdot v^2)$  shows an excellent straight line.
- The slope of that straight line is estimated to be 1.2.

#### 19.10.4 Discussion

This does not exhaust all the relationships that might be fitted to the data in Table 5 of Monk and Sullivan.

In addition, there is data in Table 6 that refers to impacts with 0.5 inch thick padding, and there is data in Table 7 that refers to impacts with 3 inch thick padding.

#### 19.11 Example 8: Fan (1983)

Values of HIC from headform impact tests at two speeds (10 mile/h and 15 mile/h) with the interior of the A pillars of two cars were reported in Table 14 of Fan (1983). The slope of  $\ln(\text{HIC})$  versus  $\ln(v)$  was about 2.3, corresponding to exponent  $n$  being about 0.8.

When the A pillar was padded with 1 inch of polyethylene foam, HIC was substantially reduced. The slope of  $\ln(\text{HIC})$  versus  $\ln(v)$  was about 4.2, which is inconsistent with the proportionality relationship obtained in section 18.5. There may have been bottoming out of the padding at the higher speed but not the lower.

Some of the impacts in the dataset of Miller et al. (1996) (see section 19.8 above) were to the A pillar, and Miller et al. make some comments specifically about this. Also concerned with A pillars, there is some data from a study using the finite element method in Figure 12 of Naick and Carnago (1998)

#### 19.12 Example 9: DeMarco et al. (2010)

DeMarco et al. (2010) reported results of drop tests of ten designs of motorcycle helmets being worn by a headform. There are several aspects of this work are worth noting.

- Approved and non-approved designs of helmet were both included. (The non-approved helmets had no or little energy-absorbing liners.)
- The impact speeds covered quite a wide range (1 m/sec to 10 m/sec).
- Coefficient of restitution was reported. Figure 4(d) of DeMarco et al. shows that it does not vary very much over a range from about 2 m/sec to 10 m/sec.
- Some of the helmet liners seemed to bottom out within the range of speeds tested.

DeMarco et al. showed interest in the functional form of the dependence of  $A_{\max}$  on impact speed. They fitted the following relationship.

$$A_{\max} \propto v^{(b + c \cdot v^d)}$$

Here, the symbol  $\wedge$  means "raised to the power", so that  $x^n$  and  $x^{(n)}$  mean  $x^n$ . (That seems a reasonable solution to the typographical problem with exponents having exponents.)

DeMarco et al. plotted  $A_{\max}$  versus  $v$  on linear axes. For two of the helmets (labelled by them as B3 and S3), the relationship appears curved, steepening considerably within the range of speeds tested. DeMarco et al. interpreted this as densification of the foam helmet liner (that is, bottoming out, or approaching it).

I have plotted the data on logarithmic axes. Certainly there appears to be a steepening of the relationship at higher speeds, from a slope of about 1.2 to a slope of about 5.3. A slope of 1.2 implies exponent  $n$  (section 18.5) is 1.5. A slope of 5.3 is incompatible with the theory.

### ***19.13 Example 10: Bonin et al. (2017)***

Bonin et al. (2017) conducted drop tests of three types of headform and four cadaver heads, wearing a single design of motorcycle helmet, at three speeds.

In the case of the Hybrid III headform, I have found the following results.

- Relationships between  $\ln(v)$ ,  $\ln(A_{\max})$ , and  $\ln(\text{HIC})$  were good straight lines. (That does not mean much with only three speeds, of course.)
- From the slope of the dependence on  $\ln(A_{\max})$  on  $\ln(v)$ ,  $n$  was estimated to be 2.9.
- From the slope of the dependence on  $\ln(\text{HIC})$  on  $\ln(v)$ ,  $n$  was estimated to be 1.9.
- The slope of the dependence of  $\ln(\text{HIC})$  on  $\ln(A_{\max})$  was estimated to be just less than 2. A true slope less than 2 would be inconsistent with the relationships of section 4.5. Thus it seems that  $n$  is very large.

### ***19.14 Example 11: Ghajari and Galvanetto (2010)***

Ghajari and Galvanetto (2010, Table 5) reported a comparison of finite element simulations of impacts of (a) a headform wearing a motorcycle helmet, and (b) a headform attached to a body and wearing a motorcycle helmet.

The results ( $A_{\max}$ , HIC, S, maximum force) were slightly different. The question arises whether a change of mass of the headform could improve the agreement of the results with the results for the full body. Ghajari and Galvanetto showed the answer is yes, the agreement of all four output variables could be improved.

Ghajari and Galvanetto used some theory to obtain their conclusions. This included assuming (a) force is proportional to deformation, and (b) effective impact speed, which makes allowance for energy absorption by the helmet shell, is proportional to nominal impact speed.

The proportionality relationships of section 4.5.1 suggest alternative methods of estimating effective headform mass (along with exponent  $n$ ) are practicable, without those assumptions being required. Since the need for an effective impact speed is plausible, a method that does not use impact speed would seem to be desirable.

### ***19.15 Discussion***

There are both positive and negative aspects to the data analysis above.

As has been seen in this chapter, extra insights into the data can be obtained by comparing it with theory. It is often practicable to ask and answer the following questions.

- Plotting the logarithms, is the scatterplot a straight line?
- What does the slope imply  $n$  is?
- When plotting the several dependent variables each versus the several independent variables, are the slopes compatible with a single value of  $n$ ?
- If not, can the theory be rescued? When trying to improve the theory, is the theory of section 18.7 (some special phenomenon at initial contact) useful?
- In view of the theory, does any of the data look wrong?

Theory helps organise the data.

But on the other hand, it seems that theory can help only a little with present-day datasets.

- Measurement of the dependent variable is often less accurate than one might wish.
- There is often only one independent variable (e.g., impact speed).
- The independent variable often has only a limited range (i.e., the lowest value is quite a high fraction of the highest), and so the slope of the scatterplot is estimated only imprecisely. Consequently, the exponent  $n$  is likely to be estimated only imprecisely.
- There is often only one dependent variable (e.g., HIC).

- There is quite often reason to doubt the validity of one or more data points.
- Reporting of the experiment, both the methods employed and the results obtained, may omit some important details.

When one sees a scatterplot, and here I am thinking of untransformed variables for which zero is a special value, specific questions are likely to suggest themselves. (a) What is the shape of the relationship: in particular, is a straight line a good description, or does the relationship appear to be curved? To convincingly answer this, it is likely that a wide range of values of the independent variable will be needed. (b) What is the relationship when the independent variable is close to zero, and when the dependent variable is close to zero? This may be of interest either for its own sake, or for what it implies about the nature of the relationship (e.g., straight line or power function) across a wide range of values of the independent variable.

There are a number of other relevant studies not included in this chapter. But my feeling is that when confronted with the present theory, it becomes plain that experimentation is a limiting factor.

- In quantity primarily: not enough tests, not enough independent variables considered, not enough dependent variables considered, not a wide enough range of speed and other inputs.
- Also to some extent in quality: accuracy of measurement, repeatability, probable errors in reporting, insufficient detail in reporting.
- Data analysis includes: forming a reasoned opinion about which data points should be excluded and which excluded (as being unreliable or outside the scope of investigation); plotting the data points in ways that reveal qualitative and quantitative regularities; comparing these with theories and models; and thereby coming to an understanding of the dataset at hand. Dealing with data in that way seems hardly more than common sense. But a broad long-lasting culture of doing that does not seem to exist.

### ***19.16 Comments on comparing data with theory***

Suppose that observations and theory agree.

- This is probably rather rare.
- It is consistent with the idea that the theory is correct and the observations mean what they are supposed to mean.
- But you can probably think of half a dozen good reasons why the observations might not mean what they are supposed to. If that is so, and these possible faults with the data have not been eliminated, it is questionable whether agreement of data with theory gives much support either to the data or to the theory.

Suppose the observations conflict with theory.

- This is probably much more common.
- However, I would not immediately regard the observations as discrediting the theory.
- The observations may be in error. Can they be made more accurately? Can some other method be used?
- The theory may be in error. Can it be extended or generalised so as to accommodate the observations? Can it be modified by mechanisms or phenomena that only occur in restricted circumstances? (For example, the beginning and the end of a series may in some way differ from the other observations.) In referring to the theory being extended or generalised or modified, I am implying quite a minor change, that leaves the core of the theory intact.

Sometimes, numerical observations are reasonably accurate, and appropriate for purpose. But even in this near-ideal situation, comparison of theory and data may not be easy. Experimentation is often difficult, and though most observations may be correct, something may have gone wrong in a small proportion of cases. With some particular type of data, past experience might suggest (for example) that perhaps 5 per cent or 25 per cent of observations are likely to be wrong.

- There may be something wrong with an observation (an outlier, as it is often called) that appears inconsistent with the other observations. One should consider whether conclusions, or perhaps failure to come to any simple conclusions, are largely due to this observation.
- Outliers tend to draw attention to themselves, and so they receive careful attention. But there may be something wrong with an observation that appears consistent with the other observations. Again, it is desirable to consider whether conclusions are relying on this observation: if it were absent from the dataset, would the conclusions be unchanged? It is an unfortunate truism that when the number of observations is quite few, a very small number of erroneous observations can distort the overall message from the dataset.

My opinion is that it is very desirable to compare data with theory. But the benefits are not necessarily what you would expect if you are concentrating on confirming or disconfirming theory. Instead, theory helps organise, plan, interpret, and understand. There will be a little more commentary in section 24.2.

The theory in chapter 18 predicts relationships between input variables (e.g., impact speed) and output variables (e.g., HIC). Regardless of the correctness or otherwise of the theory, one would expect there to be interest in the relationships between the variables listed in section 19.1. It is surprising that there are quite few usable examples.

## **Part D. Generalisation from testing in closely-specified conditions to real-world variability**

Part D has the following chapters.

20. Testing contrasted with real-world variability: Measure-generalise-cost-average.
21. Testing contrasted with real-world variability: What if several variables affect h?
22. Testing contrasted with real-world variability: Possible wider application.

Testing is an important method of improving safety. But a test is typically conducted in closely-specified conditions, whereas there is a great variety of conditions in the real world. It is to be hoped that the result of the test is also relevant to the real world. In principle, this applies to the testing of AEB systems (see chapter 6), to impact testing (e.g., pedestrian headform testing, chapter 16), and to many other types of test. There will be two aspects to the generalisation to the wider world: performance in conditions other than those in the test needs to be predicted, and then there will need to be some sort of summarising or averaging of performance in the many conditions that occur.

Section 20.6 summarises chapter 20, and also sketches how chapters 21 and 22 will supplement chapter 20.

## **20. Testing contrasted with real-world variability: Measure-generalise-cost-average**

### ***20.1 Introduction***

At present, the testing system seems to presume that the result at one 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, many other factors are taken into account, 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; Kaniathra 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 pedestrian headform impact testing (see chapter 16). I put it into the form used in section 20.4.2. Our first account of the method was as Hutchinson et al. (2012a), and this chapter is based on a later conference paper (Hutchinson et al., 2016). Chapter 19 of Hutchinson (2018) is similar to this chapter.

### ***20.2 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 (a) that there must be a numerical quantity that can be averaged, and (b) that it is appropriate to base decisions on this quantity. 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.
- 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 arguably 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.

### ***20.3 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 18). 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).

It is likely that decisions are taken based on the set of test results. For example, whether the car has passed or not, or whether this car is better than that car. Therefore 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.

## 20.4 *Equation for average cost*

Mathematical notation is used (section 20.4.2), but the meaning is spelt out in words.

### 20.4.1 Notation

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 randomly 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. (2012a). 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.

### 20.4.2 Average

The test takes place at some particular speed (e.g., 40 km/h), and  $h$  is observed. That implies 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.

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 18 for such a theory.

Equation (1) of Kianthra 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) Kianthra 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) Kianthra 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. This will be considered in chapter 21 below.

### 20.4.3 Example of calculation

Table 20.1 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 as in section 18.2.2, 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 determined empirically in a real calculation).
- 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 chapter 16). Note that if chapter 18 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  $\theta$ , it would usually be assumed that this is equivalent to a normal impact at speed  $x.\sin(\theta)$ .

Table 20.1. 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

## ***20.5 Discussion***

### **20.5.1 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. Another purpose is to permit 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.

In principle, calculation of  $A_v(p)$  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.

The above paragraphs are about differing strengths of the effect of speed. A slightly different issue is that of optimal stiffness when there are several speeds of impact. There then needs to be some sort of process of averaging over different speeds, and the relevant quantity needs to be one that can be averaged, as  $p$  can. See Appendix 9 for this.

### **20.5.2 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 20.1 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 20.1: 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. (2012a) 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.)

### **20.5.3 Further comment on the integrated assessment of primary and secondary safety**

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.

#### **20.5.4 Equivalence between impact speed and test result**

From section 18.5, the ratio of the change in HIC from a one per cent reduction in impact speed to those 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.

#### **20.5.5 Frailty**

The frailty of the person struck is important in determining the outcome. It was not considered in section 20.4.2: 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. There is further discussion in section 21.3.2.

### **20.5.6 Very stiff, contrasted with relatively soft, impact surfaces**

Ideally, good estimates of both  $h(x)$  and  $p(h)$  would be available. However, for simplicity,  $p$  might instead be the probability of death at a specified value of  $h$ . (This was mentioned in section 20.4.1.)

A possible simplification of a different kind will now be outlined.

- (a) The basis would be the high level of expertise that now exists in car design and manufacturing companies. In the future, it may be that an impact surface (e.g., a bonnet) can be assumed to have been designed so well that serious injury is unlikely from an ordinary impact. Instead, any serious injuries would probably be the result of the surface bottoming out, and the human's deceleration being due to some very stiff component.
- (b) An important consideration would be that both the effect of bottoming out on HIC, and the cost  $p$  when HIC is high, are poorly understood.
- (c) If serious injury only occurred in impacts in which bottoming out occurred, interest would be limited to these. Thus an important issue would be what proportion are these among all impacts. (And possibly the residual speed at the moment of deformation would be desired as a further factor to be taken into account.) Because of (b) above, it might be impracticable to attempt to construct a better  $p(h(x))$ .
- (d) Because of (b), there might be no attempt to use HIC. Instead, the outcome  $h$  would be the distance of deformation of the bonnet minus the distance available before bottoming out occurs. (The distance of deformation of the bonnet would be measured at a particular impact speed, and estimated for other speeds using the proportionality relationship in section 18.5.) And  $p(h)$  would be 1 for positive  $h$  (corresponding to bottoming out occurring) and 0 for negative  $h$  (corresponding to bottoming out not occurring).
- (e) Then  $Av(p)$  would be the probability of bottoming out occurring.

## ***20.6 Overview of chapter 20, and a look forward***

The tradition in testing is for conditions to be standardised. There are good reasons for this: to make comparison of objects fair, to allow designers to know what task the object needs to perform, and so on.

Nevertheless, it is easy to appreciate that this is artificial. The example in mind in this chapter is impact testing taking place at one speed, in contrast to real accidents occurring at a great range of speeds. There has been a degree of disquiet about this for some time, and the papers by Horsch (1987), Kianianthra et al. (1993), Korner (1989), Searle et al. (1978), and Viano (1988) were referred to in section 20.1.

This chapter has proposed a method of starting from a test result and generalising to a more broadly valid measure of performance. It was referred to as measure-generalise-cost-average. In section 20.4.2, the method was given in the form of a mathematical expression. That, itself, will not be intelligible to readers who are unfamiliar with that type of mathematical manipulation, but it was readily put into words.

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

Chapters 21 and 22 will deal with two supplementary lines of enquiry that arise out of chapter 20.

- In section 20.4.2, only one variable (speed) varies in the population of accidents but is the same for all tests. Chapter 21 will consider 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. These will be discussed in chapter 22. It seems possible to me that there could be much more such research that I am unaware of.

## **21. Testing contrasted with real-world variability: What if several variables affect h?**

### ***21.1 Introduction***

Chapter 20 sets out a method of calculating average performance across a range of impact speeds. The method was described by Hutchinson et al. (2012a). Lubbe et al. (2012) discussed this and other literature, and gave attention to variation in other factors as well as speed. They were most concerned with the distribution of pedestrian impact points over the front of the car. In turn, this distribution is affected by the geometry of the car, the impact speed, and the pedestrian's stature. Lubbe et al. also make passing mention of pedestrian gender and age as factors that vary. As mentioned in section 20.4.2, Kianianthra et al. (1993) had considered that crashes might vary in a number of ways (speed, impact location, impact angle), rather than only in speed.

Further, a review by Hu and Klinich (2012) particularly emphasised (a) the need to keep in mind the special characteristics of older pedestrians, and (b) bottoming out as a danger to pedestrians. Both of these issues imply the need for information beyond a test result.

The present chapter, based on Hutchinson et al. (2013a), proposes an equation that will integrate over the range of pedestrian head masses, the range of pedestrian statures, and the range of impact locations on the car, as well as over the range of speeds. To some extent, then, this is a response to Lubbe et al. and to Hu and Klinich.

Geometry of the car is not a random variable, and frailty of the pedestrian affects injury and its consequences rather than what is measured in an impact test, and these are discussed separately. The arguments are made in the context of (and with reference to the specifics of) pedestrian headform testing, but are of broad applicability in impact testing.

The specifics which are laid down in the test protocol seem to be intended to be representative of, or typical of, pedestrian impacts. Performance in other conditions is also important. Performance will be different if conditions change --- the impact will be more severe if the speed is higher --- and there are likely to be several effects.

- Low speed impacts are very important numerically. Some authors have argued that the test speeds that are used are consequently unrepresentative.
- If bottoming out did not occur at the test speed, it may do at some higher speed that is still within the realistic range. If bottoming out

did occur at the test speed, it may not at some lower speed that is still within the realistic range. In either case, there is a great change from what happens in the test.

- The A pillars are usually not tested. They are typically very stiff and receive a default fail result.
- The windscreen is usually not tested. It is typically sufficiently soft to receive a default pass result.
- Pedestrians of different statures will impact the car in different places: the taller they are, the further from the front of the car will be the impact.
- Speed will affect not only the severity of the impact at a given location, but also the location that is struck.
- A change of the effective head mass is likely to have different results at different speeds and different locations. An increase of effective head mass will lead to acceleration taking place over a longer distance. At low speed and with plenty of clearance distance under the bonnet, that will mean lower accelerations. But at high speed and with little clearance distance under the bonnet, the increased distance will make bottoming out more likely, and hence a great increase in severity.
- Technology such as autonomous braking or improved tyres may substantially reduce impact speeds. Lubbe et al. (2012) note that passive and active safety systems cannot be assessed by a straightforward combination of distinct methods.

## ***21.2 Extensions of measure-generalise-cost-average***

### **21.2.1 Notation**

Notation is given below.

- $x$ : speed of impact of the car with the pedestrian (it is assumed this is the same as the speed with which the head hits the car)
- $m$ : effective mass of the pedestrian's head
- $s$ : stature of pedestrian
- $i$ : location on the car (this is a categorical variable, a name rather than a number)
- $u$ : distance of the head impact point from the front of the car
- $w$ : distance of the head impact point from the side of the car, laterally across the car
- $h$ : HIC, the Head Injury Criterion
- $p(h)$ : utility or cost of  $h$  (or, rather, the average of this, as the injuries and outcomes will vary according to factors outside the scope of the present discussion)
- $f(x)$ : probability density function of speed  $x$
- $g(m, s)$ : joint probability distribution of head mass  $m$  and stature  $s$
- $z$ : frailty (which will be discussed in section 21.3.2)

In pedestrian headform tests, HIC is used to characterise the test result. This is not essential, though, and  $h$  could instead be the maximum acceleration or some other summary.

### 21.2.2 Overview of calculation

Chapter 20 was chiefly concerned with the effect of speed, and had the expression  $p(h(x)).f(x)$  for the cost corresponding to speed  $x$ . (Notice that it is assumed that  $h$  alone determines  $p$ : the other variables have their effects on  $p$  because they affect  $h$ .) In section 20.3, the general strategy of the calculation was referred to as measure-generalise-cost-average. If location  $i$  on the car is represented in the expression, the equation for average cost in section 20.4.2 will be as follows.

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

Locations on the car differ in how safe or unsafe they are. Chapter 20 regards the location on the car as being the basic unit to analyse.

However, Lubbe et al. (2012) say that averaging over the whole car is important (this is particularly so because change to the distribution of speeds will change the distribution of impact locations), and so is averaging over pedestrian head mass and stature. An expression of similar form will be obtained below that applies to the car as a whole.

### 21.2.3 Conditions that vary

Quantities that vary in the real world, and over which the cost should be averaged, are listed below, with a short description of how they have their effects.

- Speed of impact. Firstly, at any given location on the car, HIC increases with increasing speed. Secondly, the impact location of the head will be further from the front of the car, the higher the speed is.
- Mass of pedestrian's head (effective mass, that is). HIC depends on mass as well as on speed.
- Stature of pedestrian. The impact location of the head will be further from the front of the car, the taller the pedestrian is.
- Impact location on the car. Each location on the car may be different in respect of both the surface (e.g., the bonnet) and what is underneath (e.g., the engine). The distance  $u$  of the head impact point from the front of the car is not random, being determined by impact speed and pedestrian stature, but the distance  $w$  of the head impact point from the side of the car is a random variable. Possibly impact angle (angle to the vertical, that is) should be included also, but this will not be considered below.

These effects are represented in mathematical notation as follows (the symbols are as listed earlier).

- Speed. Firstly,  $h(x)$ . Secondly,  $u(x)$ .
- Mass.  $h$  depends on  $m$  as well as on  $x$ :  $h(x, m)$ .
- Stature.  $u$  depends on  $s$  as well as on  $x$ :  $u(x, s)$ .
- Impact location.  $h$  depends on location:  $h(x, m, i)$ .

#### 21.2.4 Expression for the average of $p$

The expression  $p(h(x))$  shows that  $x$  affects  $h$  and this in turn affects  $p$ . To include the extra variables, this may be generalised as below.

- $p(h(x, m, i))$  shows that mass affects  $h$  and hence  $p$ .
- $i$  is defined by the distances  $u$  and  $w$ , along and across the car. Thus  $p$  becomes  $p(h(x, m, i(u, w)))$ .
- $u$  is determined by  $x$  and  $s$ . Thus  $p$  becomes  $p(h(x, m, i(u(x, s), w)))$ .
- This will need to be multiplied by the probabilities with which  $x$ ,  $m$ , and  $s$  occur:  $p(h(x, m, i(u(x, s), w))).f(x).g(m, s)$ .

Finally, average  $p$  is obtained by integrating over the four quantities  $x$ ,  $m$ ,  $s$ ,  $w$ . The equation (below) applies to the car as a whole. (The equation in section 20.4.2 applies to a particular location on the car.)

$$Av(p) = \int \int \int \int p(h(x, m, i(u(x, s), w))).f(x).g(m, s).dx.dm.ds.dw.$$

As mentioned in section 20.4.2, an equation in Hamacher et al. (2011) is similar in principle.

#### 21.2.5 Comments

Different probabilities of different  $w$  are not shown in the equation. It would be necessary to do so if some locations across the width of the car were struck more frequently than others. (In addition, it may be the case that narrow cars miss some pedestrians that wider cars would hit. It is probably more convenient to take account of this via reduced impact frequency rather than by setting  $h$  to 0 for impacts that are avoided.)

The effective head mass  $m$  and the pedestrian's stature  $s$  may not be independent, in which case  $g(m, s)$  will be a complicated bivariate probability density, but lack of information may mean the use of the product of probability densities of  $m$  and of  $s$ ,  $g_1(m).g_2(s)$ .

## 21.3 Discussion

### 21.3.1 Data requirements

The expression  $p(h(x)).f(x)$  (chapter 20) requires good data on the functions  $h(x)$  and  $p(h)$  and on the probability density  $f(x)$  if the result is to be accurate in absolute terms. What Lubbe et al. (2012) call for, and is given in section 21.2.4, requires in addition good data on the dependence of  $h$  on  $m$ , the dependence of  $u$  on  $x$  and  $s$ , and the bivariate probability density  $g(m, s)$ . These are severe demands, but are not out of the question. This is so especially since improvement in the comparability of vehicles and usefulness of impact test results may occur even if the numerical magnitude of  $Av(p)$  is not accurate in absolute terms.

The equation (section 21.2.4) should not receive the blame for broader limitations of the testing system. The system aims to make cars as safe as is reasonable, and there is tacit acceptance that the test result would be very bad at a high speed of impact. The equation at least draws attention to the many cases occurring at low speeds of impact and the very high severity of the cases occurring at high speeds of impact, instead of ignoring all these in favour of a result at one speed.

### 21.3.2 Frailty

Injuries, outcomes, and therefore costs vary from person to person, even if they are of the same stature and effective head mass, and strike the same location on the car at the same speed and angle. This may be ascribed to location on the head of the impact, to differences in frailty, and perhaps to some other factors. "Frailty" here may have a limited meaning (bone strength, resistance to infection, and so on), or may be a catch-all term referring to any aspect of a person's reaction to applied physical force. Frailty is not recorded in road crash statistics, but perhaps age could be used instead. It should also be noted that in the present context, frailty is something other than stature and head mass, as these are already included in the expression given.

Variability in frailty is not treated in section 21.2.4 in the same way as variability in speed, stature, and head mass. The reason is that variability in frailty is presumed to be taken account of by using an average cost function  $p(h)$ . That is, frailty does not affect HIC, or whatever other summary of the physical aspects of the impact is being used. Rather, frailty affects the human's reaction to HIC: with  $z$  being frailty,  $h$  is still  $h(x, m, i)$ , not  $h(x, m, i, z)$ , and frailty would be introduced by writing  $p(h, z)$ . Expressed in other words, an impact location that is safer than another for one level of frailty is expected to also be safer for all other levels of frailty; the same cannot be said about speed or head mass. Furthermore, if the distributions of  $x$ ,  $m$ , and  $s$  are independent of  $z$ , it is sufficient to use

$p(h)$ , with this having been averaged over  $z$ . If the distributions of  $x$ ,  $m$ , and  $s$  are different for people of different frailties, then the product of cost and its probability should be shown as  $p(h, z).f(x, z).g(m, s, z)$ . But this is impracticable --- it is far too demanding of data.

### 21.3.3 Is this greatly over-simplified?

The general idea in this book is that the function  $h(x)$  is a simple one, and that the functional form is the same for all the points of impact, so that the test result is sufficient to tell us what  $h$  is at any other impact speed. That may not be true. For example, there may be plenty of space under some impact points and very little under other impact points. At the latter, bottoming out would occur with only a little increase in speed. Section 20.5.3 drew attention to a strategy described by Ferenczi et al. (2015) and Wimmer et al. (2015) that assumed the availability of detailed information about road user behaviour and vehicle construction.

How might a testing regime operate if the various functions  $h(x, i)$  had a complicated dependence on  $x$  that was different for each impact point  $i$ ? A similar question was asked in section 11.7 in the context of testing AEB systems. A possible answer is as follows.

- The testing authority would require the vehicle manufacturer to estimate the function  $h(x)$  at each impact point. This might even extend to also estimating  $h$  for different values of other variables, such as  $m$ . The estimates would be based on calculations of deformation during impact, that would be based on details of vehicle design and material properties that the manufacturer would know.
- The testing authority would take a random sample of impact points and speeds and in each case carry out a real physical test, as a check on the estimates provided by the manufacturer. If the estimates were sufficiently close to the results, the estimates would be accepted. If, on the other hand, there were substantial differences between the estimates and the results, some correction would be applied.

As described by Ponte et al. (2013, especially p. 8), a procedure of Euro NCAP seems quite similar to this in spirit, though only one speed is considered.

## 22. Testing contrasted with real-world variability: Possible wider application

### 22.1 Introduction

In chapters 20 and 21, I am thinking chiefly of a pedestrian's head striking a vehicle exterior, or of an occupant's head striking a vehicle interior. But the method of section 20.4.2 might be relevant to many fields of testing, if there is appropriate interpretation of the functions  $h(\cdot)$ ,  $p(\cdot)$ , and  $f(\cdot)$ .

There are various other contexts in which the mitigation of impact is important. In several of these there is a contrast between testing being conducted at a standardised level of violence and real-world impacts occurring at many different levels of violence (Hutchinson et al., 2012b).

- *Other types of impact causing severe injury.* This context is the most similar to testing of car exteriors with a headform: testing is conducted of padding materials for vehicle interiors, restraint systems such as seat belts and air bags, and of various types of protective helmet. Injuries to not only the head, but also to the limbs and body, are also protected against by padding and cushioning.
- *Repeated impacts gradually causing injury.* Examples are running shoes and keyboards. (Section 11.8 of Hutchinson, 2018, has an example on repetitive impacts of the foot and leg.)
- *Handling and packaging of manufactured items.* These might be large and relatively robust or small and delicate. (Chapter 17 of Hutchinson, 2018, is relevant to this topic.)
- *Handling and packaging of fruits and vegetables.* There are various stages, from the field to the home. (Chapter 18 of Hutchinson, 2018, is relevant to this topic.)
- *Railway buffers, buffer stops, and analogous equipment.*
- *Manipulation of items by robots.* If one item is to be fitted to another, it is usually desirable that initial contact is not violent.
- *Inadvertent impact of robots with humans.* (Sections 13.7 and 14.6 of Hutchinson, 2018, have examples on this.)
- *Damage from hail or raindrops.* (Section 17.8 of Hutchinson, 2018, has examples on hail.)
- *The fall of rocks weighing several tonnes on to roads and other structures.* (Section 17.11 of Hutchinson, 2018, has examples on this.)
- *Impact with undersea pipelines.* (Section 17.12 of Hutchinson, 2018, has examples on this.)
- *Collisions between building structures when they are moving in an earthquake.*

- *Impacts of birds with aircraft.* (Section 17.15 of Hutchinson, 2018, has an example on this.)
- *Undesirable powdering* of bulk materials during transportation and processing.

Except where head injury is the concern, maximum acceleration is nearly always the quantity to be minimised.

Obviously I am thinking of mechanical impact and cushioning. I do not know if there are useful analogies in, say, electricity or hydraulics or chemistry.

It was said in section 20.2 that measure-generalise-cost-average is not very different from any procedure in which two or more tests are conducted and the results weighted. Some particularly similar ideas are discussed in this chapter. The most similar set of calculations that I have come across will be summarised in section 22.2. Sections 22.3 and 22.4 have some notes about packaging of manufactured items and the testing of people or groups of people.

## ***22.2 Experimental injury and average effect on a human***

### **22.2.1 Kokinakis and Sperrazza (1965)**

Experiments relevant to penetrating injury are conducted in which small missiles (representing bullets or shrapnel, for example) are fired into a tissue simulant such as gelatin. (Chapters 15 and 16 of Hutchinson, 2018, are relevant to this topic.)

Is it possible to infer, from a small number of tests, what the average effect would be on the human body? This was considered by Kokinakis and Sperrazza (1965). The description of this in their report appears very different from the method of section 20.4.2, but in Hutchinson (2015b) I argued there is a core similarity.

In the context considered by Kokinakis and Sperrazza, the several functions are interpreted as follows.

- $h(x)$  is the wound received (the name of the injury, or a description) when someone is struck at location  $x$ ;
- $x$  is the name of the part of the body struck;
- $p(h)$  is the level of incapacitation (a percentage);
- $f(x)$  is the probability of  $x$  being the part of body that is hit.

The result of the calculation is the average level of incapacitation.

As with the head impact context, there is difficulty in establishing a credible function  $p(h)$ . Kokinakis and Sperrazza refer to using medical

assessors who estimate physiological effects in soldiers subjected to many hypothetical wounds, and to establishing a consensus of medical assessors and combat personnel on the percent disability (for a given tactical situation at a given time after wounding).

### 22.2.2 Examples of subsequent work

There is continuing interest in this. VanAmburg (2011) estimates the likely level of injury at different impact points of a fragment on the limbs or face. The calculation is then taken a step further, to give a probability over a random point of impact of a specified level of injury. In the present terminology,  $p(h(x))$  is 1 if the AIS (Abbreviated Injury Scale) score corresponding to  $h(x)$  is at least 3, and is 0 otherwise, and the probabilities of different impact locations  $f(x)$  are assumed equal.

Tan et al. (2017) had software that was able to calculate various outcomes from a projectile (e.g., bullet or fragment) hitting a head. The calculations were performed for thousands of different trajectories of the projectile. The head was represented as wearing one of several helmets. One of the calculated outputs was head-to-helmet spacing, which might be positive (space maintained between head and helmet) or negative (impact of helmet with head, implying injury of severity related to the implied deformation of the head). The distributions of this quantity for different helmets were illustrated by Tan et al. The characteristics of the helmet (including how much of the head it covers, and whether it has padding) obviously play a big part in determining the results of the calculations. Although testing is, no doubt, important in establishing some of those helmet characteristics, testing is not so central in this context as it is in chapters 20 and 21. And Tan et al. do not convert the calculated outputs to costs and average them.

### 22.2.3 Several stages of costing

The conversion of  $h$  to  $p$  may be referred to as costing or valuation of  $h$ , the proxy for injury. This is represented as having only one stage, the utility or cost  $p(h)$ . However, this might be split up. The following set of stages is an example.

- A particular named injury (e.g., skull fracture) might be likely at a given level of HIC;
- That injury might have a particular outcome (including a certain number of days in hospital, and a certain number of days off work); and
- That outcome might have a certain cost or disutility (including economic losses and a monetary equivalent of pain and suffering).

I have not thought it worthwhile to split  $p(h)$  into several stages, but something similar is done in the vulnerability/lethality context: "target damaged components" lead to "target measures-of-capability", which in turn lead to "target measures-of-effectiveness (utility)" (Deitz, 1998).

### ***22.3 Packaging of manufactured goods***

Hutchinson et al. (2012b) noted that packaging engineers make use of the "cushion curve". This is a plot of the outcome of an impact (usually maximum acceleration) versus static stress (which is often on a logarithmic scale). It usually refers to results of testing, with different curves referring to different drop heights of an impactor corresponding to the relevant static stress. The curve is U-shaped because of bottoming out (Wyskida and McDaniel, 1980, especially p. 103). Static stress is analogous to headform mass, and drop height is analogous to speed. (Bottoming out may be qualitatively different when foam or something else is being crushed between two stiff surfaces, rather than a car bonnet bending until it comes into contact with a stiff structure.)

The hostility of the environment is also of interest. This might be summarised by, for example, the distribution of heights from which a package might fall or be dropped (Peaché, 1986, Figure 4). It is thought that when being handled by humans, small packages tend to be dropped from greater heights than large packages, i.e., the mean of the distribution is greater. A distribution of drop heights is very similar to a distribution of impact speeds in chapters 20 and 21.

A procedure suggested by Burkhard (1966, pp. 169-170) is worth mentioning. The context was shock and damage to hearing aid transducers. I am unable to understand exactly what Burkhard meant. The following is my interpretation of what he intended to say.

- Each transducer has a fixed tolerance for acceleration. Failure occurs if tolerance is exceeded. Tolerance varies between specimens of the transducer.
- In what follows, the notation (symbols  $x$ ,  $p$ , and  $f$ ) will be chosen so as to emphasise similarity with section 20.4.2.
- Let  $p(x)$  be the cumulative distribution of tolerance. That is, the proportion of transducers with tolerance less than  $x$  is  $p(x)$ .
- Consider a period of time, e.g., one year, and the maximum acceleration a transducer is exposed to in that year. Let  $f(x)$  be the probability density function of the maximum acceleration.
- For any  $x$ ,  $p(x).f(x).dx$  is the proportion of transducers that experience  $x$  as the maximum acceleration in the year and have a tolerance less than that, and thus fail. (I should say:  $p(x).f(x).dx$  is the proportion of transducers that experience maximum acceleration between  $x$  and  $x+dx$ , the increment  $dx$  being small, and have tolerance less than that, and so on.)

- The area under the curve representing the product  $p(x).f(x)$  is the integral  $\int p(x).f(x).dx$ . As Burkhard says, this is proportional to the number of transducers that fail in the relevant time period.
- In Burkhard's Figure 3, curve 1 is an example of  $p(x)$ , curves 2 and 3 are examples of  $f(x)$ , and curves 4 and 5 are examples of the product  $p(x).f(x)$ .

The results of testing enter via observing sufficient tests (fail vs. tolerate an acceleration) to construct the cumulative distribution of tolerance  $p(x)$ . This is a little different from observing a test result (for example,  $h(40)$ ) and extending that into a function  $h(x)$ . Burkhard had in mind a sensitive component being packaged within a case in order to be used, and Sheehan (1988) describes the above method in the context of packages being transported.

This might be described as a stress-strength model. A name like that, though, tends to suggest similarity and symmetry between stress and strength. But strength is observed by testing in a laboratory, whereas stress is estimated by in some way taking a sample from the environment; even if there is no positive reason to doubt the correctness of both measurements, the methods are likely to be different, which raises the question of comparability. My feeling is that to identify a situation as being analogous to a stress-strength model does not solve the problem; rather, it is like the equation in section 20.4.2 in that it is the first step on quite a long road towards solving the problem.

## ***22.4 Testing of people***

### **22.4.1 Background: The slope of the dependence of $h$ on $x$**

The physical measure of performance  $h$  depends on the quantity  $x$  that varies in the real world but is the same for all tests. For example, in a pedestrian headform test, HIC depends on impact speed. Now consider how strongly  $x$  affects  $h$ , that is, the slope of the relationship. It may be asked whether the slope is the same for all items that are tested (that is, in the notation of section 21.2, for all  $i$ ).

If the slope is approximately the same for all items tested, calculation of  $Av(p)$  (as in sections 20.4.2 and 21.2.4) for two items has the benefit of quantifying the comparison between them. This may be useful in itself or as input into a decision along with other considerations such as (for example) the cost of the two items.

Alternatively, suppose the slope does depend on which item is tested. The two functions  $h(x)$  for two items will cross over, and item 1 will be better than item 2 for one value of  $x$ , and item 2 will be better than item 1 at another value of  $x$ . In this case, calculation of  $Av(p)$  will be even more

important, as otherwise these very different outcomes at different  $x$  will not be given their appropriate importance.

The possible occurrence of this phenomenon in the headform testing context was discussed in section 20.5.1. It is mentioned again now as introduction to considering testing of people or perhaps groups of people working as a team. (This was discussed by Hutchinson et al., 2013b.)

The function  $h(x)$  is a generic measure of performance. In impact testing,  $h$  is usually a measure of how severe the impact is: the smaller, the better. In some other contexts, it is usual for performance to be measured in such a way that the higher, the better, and that language will be used below.

### **22.4.2 Floor and ceiling levels of performance**

A "floor" and a "ceiling" to  $h(x)$  refer to levels of performance in, respectively, the most difficult and the easiest conditions. It is common to think that someone of higher ability than another, as evidenced by better performance on tasks of average difficulty, will be better at difficult tasks of the same type and at easy tasks of the same type. But this is an incomplete account if people may differ in respect of their floor level of performance and their ceiling level of performance, as well as in their typical level of performance.

Consider easy tasks that almost anyone can succeed in. Whether or not these are actually successfully performed may depend largely on characteristics usually thought to be part of personality rather than ability: being attentive and careful and avoiding silly mistakes.

Consider difficult tasks that almost everyone will fail at. The degree to which these are successfully performed may again depend largely on personality characteristics: willingness to have a go, creativity, psychological acceptance of partial success, perseverance, persistence, and so on. (In many testing situations, success may also occur from random guessing.)

Thus  $h(x, i)$  (referring to person  $i$ ) and  $h(x, j)$  (referring to person  $j$ ) may cross over. The relative proportions of real-world tasks that are of average difficulty, are easy, or are difficult will determine how important are the three characteristics. Names for the three characteristics might be ability, carefulness, and persistence. In such a case,  $h(x, i)$  would need to be obtained from three test results  $(x_1, h_1)$ ,  $(x_2, h_2)$ , and  $(x_3, h_3)$  (or perhaps from  $(x_1, h_1)$  together with measurements made, by quite different methods, of carefulness and persistence).

If performance is expressed as a probability or proportion (of succeeding in a task, for example), it will necessarily have both a floor and a ceiling, as probabilities are between 0 and 1.

### **22.4.3 Inverted U-shaped dependence**

Inverted U-shaped dependence of  $h$  on  $x$  means that performance  $h$  is highest in the middle of a range of  $x$ , with performance being lower for both low values of  $x$  and for high values of  $x$ .

Stress and similar concepts are important examples of conditions. Human performance is commonly said to be best when stress or arousal or stimulation is moderate, and lower both when one is too sleepy or too excited. That is, stress / arousal / stimulation has an inverted-U effect on performance. Testing people at one value of arousal will not give sufficient information about how they perform across the range of levels of arousal, or what their average performance will be.

More broadly than optimal arousal,  $h$  may be a decreasing function of how different the task is from the task the person is best at. That is, it may be desirable to match the exact conditions and nature of the task to the idiosyncrasies and abilities of the person.

An inverted U-shaped dependence will make it quite likely that two different  $h(x)$  functions will cross over.

### **22.4.4 Heat strain**

Above,  $x$  was thought of as task difficulty or arousal. It might instead be some aspect of the environment. Temperature, for example, is important to humans and to human performance. People and their clothing (e.g., protective clothing) may be tested at one temperature, but it is expected that they do not suffer hyperthermia and do perform their task satisfactorily over a range of temperatures.

Heat strain models have been developed to predict body temperature from such factors as metabolism (which in turn will depend on body weight, weight of load, intensity of exercise, and so on), the environment (dependent on temperature, the insulation of the clothing, and so on), and available cooling (dependent on the permeability to water vapour of the clothing, humidity, wind speed, and so on). Such models could be viewed as analogous to  $h(x)$ .

## Part E. Ending and Appendices

Part E has the following chapters.

23. Some other specific theoretical issues in road safety: For the future?
24. Concluding comments.

The following are the Appendices.

25. Appendix 1: Further results relevant to the effect of mass ratio on injury severity.
26. Appendix 2: Newton's equations of motion.
27. Appendix 3: Test results of Seiniger and Gail (2015) viewed abstractly.
28. Appendix 4: Data on the effect of car mass on injury severity.
29. Appendix 5: Improvements in the design of cars for pedestrian impacts.
30. Appendix 6: Behaviours as proxies for accidents.
31. Appendix 7: Some difficulties with accident rates.
32. Appendix 8: Induced exposure.
33. Appendix 9: Stiffness when there are several speeds of impact.

## 23. Some other specific theoretical issues in road safety: For the future?

This chapter is not concerned with criticising and suggesting how improvement might be made to the treatment of the topics considered in this book --- for example, model [A] of sections 5.2 and 8.1 and alternatives to it, or the differential equation of section 18.4 and alternatives to it. Instead, several quite different issues are discussed. I should add that although I would like to see progress with them, I am sceptical about prospects in the immediate future.

The issues considered may seem a slightly odd selection. I think that is because they have an important theoretical aspect (in my opinion), rather than being a wide-ranging list of questions where advance is desirable. In contrast, probably the great majority of interesting road safety research questions are empirical or practical in nature. (And many interesting theoretical questions relevant to road safety are not what I would call road safety theory, but psychological or behavioural theory.)

### 23.1 *Gap acceptance*

A distinctive feature of this book, perhaps surprising to the reader, is the concentration on the last fraction of a second before impact, after an emergency has arisen, and on the impact itself. Thus model [A] (section 5.2 and section 8.1) concentrates on the reaction by a vehicle or its driver to an obstacle directly ahead.

Now suppose, instead, we consider the obstacle that is in the path of a vehicle. Why was the obstacle present, that is, how was the emergency initiated? Some readers, perhaps, thought that most of this book would discuss that, but I can only offer some preliminary comments. Probably the most frequent reason is that the obstacle 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 is not seen (blind spots).

It is possible that data collected in the course of in-depth at-scene crash investigations will prove useful for understanding both the reactions of drivers to obvious danger, and gap acceptance errors.

Where were the vehicles (or crash participants) when there was first a line of sight between them; for each participant, did they in fact see the other, and when; where were the vehicles when imminent danger should have been appreciated; for each participant, did they in fact appreciate danger; what happened then (the actions taken, such as strength of braking).

In some cases, there is objective evidence about such questions, and participants may have some relevant memory.

Research of that general type has been conducted, despite the difficulties.

In the context of AEB, examples include Hamdane et al. (2015), Jeppsson et al. (2018), and several discussed in section 6.4.

My impression, though, is that the work is usually tightly focused on things like distances and speeds at a specific moment. In contrast, what I am hoping for is something broader --- perhaps a construction of a sequence of events that occurred accompanied by an appreciation of events that did not occur but might have.

Such research uses a lot of information about what happens in real crashes, and in that sense is realistic. My opinion is that it is useful in understanding the effects of details of the operation of AEB on the details of how many lives are saved and injuries prevented. But in broad terms, the example in section 5.2 suggests that the result is a foregone conclusion: (a) if it is assumed that the AEB system has a high specification and works well, then it will be predicted that impact speed is substantially reduced in many cases, and (b) if impact speed is reduced, then if the usual assumption is made that probability of death is strongly dependent on impact speed, it will be further predicted that a high proportion of deaths will be prevented.

Below is a list of four possible reasons why the obstacle was present. (The first is that already discussed.) 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. For example, the obstacle is a vehicle that is out of control.

This chapter is supposed to be about theoretical issues, yet the questions raised above are largely empirical. Yes, but I think it is not clear how to structure an answer to the question (of why and how an obstacle came to be present), and structuring an answer counts as theory. I am suggesting (a) reasons why the obstacle was present, and (b) in the case of the obstacle being present deliberately, a detailed examination of the sequence of events, as recorded in an in-depth at-scene database. And that approach may be relevant to theories of human error (section 23.2).

## **23.2 *Human error***

As far as I know, theories of human error in gap acceptance have not yet become popular. I can imagine some reasons.

- Some people appear to tolerate a very narrow margin of safety --- the distinction between a successful and an unsuccessful action may be tiny.
- Routine accident data is not well-suited to studying the problem.
- 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).
- It is difficult to do experiments (e.g., using a driving simulator or virtual reality).
- It is tempting to instead do something immediate and practical about road safety.

Stanton and Salmon (2009) reviewed methods of classifying human error, particularly those broad methods associated with the names of Norman, Reason, and Rasmussen, along with several others that are more specific to vehicle drivers. My present opinion is that the broad methods are not attractive for application to road safety. I am chiefly thinking of the methods insofar as they refer to people in the crash, and to the errors they make, not to risk on the road more generally.

I am hesitant to be so dismissive, and perhaps I should be positive and suggest how to begin classifying human error.

1. Be clear what type of crash is under discussion. Following on from section 23.1, the natural type of accident to give as an example is an obstacle (pedestrian or vehicle) moving into the path of a vehicle.
2. 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.
3. Restrict attention to short-lasting actions (and consider separately relatively long-lasting states such as speeding).
4. 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.
5. Distinguish between (a) errors of omission, and (b) errors of commission.
6. And then the list in section 23.1 will suggest such categories as sensory, judgment, decision-making, and execution errors.

These are very tentative suggestions. I have made this list because this book is largely concerned with events after a potential emergency has arisen, but I would like to know more about generation of emergencies. 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. My point is not to seriously propose the above list, but to say that I cannot see much compatibility between it and the several methods described by Stanton and Salmon.

Perhaps more attention should be paid to the causation of accidents. Causation has been rather neglected for 50 years or more. There are good reasons, including that numerous causative factors often contribute to accident occurrence, and causation is often poorly represented in routine accident data, as it is rather subjective. But it may be that the accident data issues have inhibited the study of causes in other respects. There is a possibility that other types of data will be more helpful: from in-depth at-scene crash investigations of the type developed several decades ago, from other detailed crash investigations, from instrumented vehicles driven by ordinary drivers in ordinary traffic conditions, from cameras on the street, and perhaps other sources.

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 section 11.5 of this book, Lee, 1976, and

Stewart et al., 1993.) These might be components of some future account of gap acceptance and human error.

Summing up sections 23.1 and 23.2, I feel that the last moments before impact (about a second) can be described by something in the style of model [A] of sections 5.2 and 8.1. (Many other people have thought the same.) The next step is to look more closely at the process of the driver perceiving an obstacle and reacting to it, and at the reasons for the obstacle being there. The big question in my mind is not whether model [A] is roughly correct or not; it is rather whether reality is so complicated and variable that any model is unlikely to be helpful.

### ***23.3 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. I have in mind that maladaptation may occur in a variety of traffic circumstances: driving a vehicle that has (or is perceived to have) extra safety features is an example, but there are many others.

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. And pedestrians may fail to pay proper attention in streets where there are many pedestrians and a low speed limit --- yet even a low-speed accident with a truck can be fatal, because of the possibility of run over.

These types of maladaptive behaviour 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.

At present, I do not view maladaptation as a serious threat to the effectiveness of AEB, as I imagine that AEB will not usually be in a driver's mind, and a driver will not have experience of AEB having

operated successfully. Thus confidence that AEB will operate successfully in the future will not be in the driver's consciousness. The situation may be different with some other safety systems, such as adaptive cruise control. A driver may be aware that such a system is operating, and become confident or over-confident in its effectiveness and reliability.

- Even though I am rather sceptical about the more ambitious claims made for autonomous operation of vehicles, I can imagine ways in which such systems could improve safety. For example, they could keep the vehicle within the speed limit, they could choose a lower speed than a human driver, or follow at a greater distance, or avoid accepting a risk, or receive and accept an advisory speed (based on, for example, when the next traffic light will be green).
- That being so, it is easy to imagine that some drivers may drive near to the limit of what the system will accept. Understandably, then, some researchers think that how road users adapt (or adapt dangerously) to advanced driving aids is a topic of the first importance.

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.

### ***23.4 Behaviours as proxies for accidents***

The public and road safety professionals often want to know whether some change (e.g., to road design, or to traffic law) has or has not improved road safety. More broadly, the evaluation of health and social interventions is an enormous subject. Theory is an aid to evaluation.

Much road safety work concerns a particular category of road users in a particular city or state. Thus, despite the great number of road accidents in aggregate, lack of direct data from road accident numbers is often a problem. It would be useful if data could be collected on some form of behaviour that could be regarded as a near-accident, as a proxy for an accident, or as increasing risk. Traffic conflicts (near misses) are an example. Oppe (1985), though, makes the point that the conflict method should not only count conflicts, but study and understand them, and that systematic observation of critical traffic events is a better term.

Hall and O'Day (1971) argue that a "causal chain" is a useful tool when evaluating interventions. By this they mean a list of events from an intervention to accident and injury occurrence (or non-occurrence). For example, mass media publicity and police activity might both affect a driver's attitude to driving speed, the attitude affects driving speed, driving speed affects degree of success in reacting to an emergency, and so on. A reduction of driving speed might be seen as strong evidence for reduction in expected number of accidents and fatalities. Reporting, in

answer to a survey question, having heard or seen the publicity or the police activity is more distant from an accident, and is weaker evidence.

- My opinion is that clarity is very important when expressing a theory, by means of a causal chain or otherwise.
- Hall and O'Day expressed causal chains as flow diagrams, with boxes (containing text) connected by arrows.
- Hall and O'Day did not define what they meant by the boxes or the arrows. I rather dislike flow diagrams because that is such a common fault. My opinion is that there is a high risk of imprecise thinking when definitions are omitted.
- Some people might say that the paper by Hall and O'Day was published decades ago, and causal chains would be more prominent in road safety work if they were indeed useful. There are several responses to this. (a) Causal chains and proxies for accidents are used to some extent. (b) They might be used more if applied with greater clarity of expression. (c) They may be used more in the future, with advances in technology for data acquisition.
- And with much road safety work, there seems to be some sort of causal chain in the background. Mass media publicity, referred to above, is an example.

My chief point is not to claim causal chains are useful, or are ready for further theoretical development. (Indeed, I think causal chains are avoided in some contexts, as insufficiently capturing the complexity of causation and influence.) Such claims seem too ambitious and too vague. Instead, my point is that better knowledge of behaviours closely related to crashes is desirable.

There are several types of event that might be considered similar to accidents.

- Traffic offences are an example: the behaviour certainly may be similar. It is sometimes possible to study traffic offences using data collected routinely: the records may be held by the driver licensing authority.
- Traffic conflicts might be observed in a special-purpose study at a particular site.
- Behaviours such as speeding, drink-driving, and failing to wear a seat belt may similarly be observed.
- Attitudes to behaviours may be expressed and recorded, using a questionnaire, for example.

Appendix 6 continues the discussion of this.

For traffic offences, see also Kloeden et al. (2008). These authors asked whether, if an intervention is shown to affect the number of driving offences, that is also evidence that it has an effect on road crashes. It is fairly frequent that an effect is found on offences but not on crashes. Kloeden et al. felt that the question remains open as to whether there typically is a (smaller) effect on crashes, or whether there is typically no

effect on crashes because the behaviours targeted are not sufficiently relevant.

Detailed comparison of the characteristics of different types of accident and different types of offence might be fruitful. I say this because of interesting results given by Kloeden (2008) concerning contrasts between offences involving a behavioural choice, those involving a lack of driving skill, and those of a largely administrative or financial nature. Kloeden found that speed offences, seat belt offences, and alcohol offences rise over the years after a young person gets their driving licence. In contrast, offences involving a moving violation fall over the years following licensure, and so did casualty crashes. Crashes involving turning right through oncoming traffic and crashes involving hitting a fixed object showed a particularly sharp decline.

It might be thought that near-crashes largely occur when a driver is not attentive, and that crashes largely occur when a driver is attentive.

- If being not-attentive is reasonably frequent and is much more likely to generate a near-crash, then near-crashes will indeed largely occur when a driver is not attentive. For example, this is so if being not-attentive occurs 5 per cent of driving time and is 50 times more likely to generate a near-crash, or occurs 40 per cent of the time and is 3 times as likely to generate a near-crash.
- But concerning crashes, in many of these the driver being discussed is an innocent party, and mostly occur when he or she is attentive simply because he or she is attentive most of the time. The corresponding group of near-crashes --- that is, in which the driver being discussed is an innocent party --- is unobserved. (I have in mind that, as in the report referred to in the next paragraph, there is a particular group of drivers whose driving, near-crashes, and crashes are being observed.)

This would suggest that when focusing on a set of drivers, near-crashes are not suitable proxies for crashes.

The arguments in the previous paragraph occurred to me when reading Wood and Zhang (2017).

- However, it is not clear to me whether Wood and Zhang were intending to say this, or whether it is supported by their data.
- Using naturalistic driving data, Wood and Zhang found a negative relationship between perception-reaction time and deceleration for crashes, but a positive relationship between perception-reaction time and deceleration for near-crashes.
- At p. 2 of their report, Wood and Zhang seem to suggest that for attentive drivers, the negative relationship is a consequence of the driver's perception of the risk of the situation. The positive relationship is a consequence of failing to appreciate danger until it is nearly too late.

### ***23.5 Injury accidents as proxies for fatal accidents***

There is a range of severities of accidents.

- Fatal. These are of most importance. There are relatively few of them.
- Non-fatal injury. In advanced countries, there is usually quite a lot of information about such accidents. It is usually collected routinely by the police, and passed on to local government and to the Ministry of Transport or similar body.
- Damage-only. Police may collect some information on non-injury accidents. Insurance companies are another possible source of information.

Very often, decisions (e.g., about road improvements, and about road safety laws) are taken with the great majority of the empirical evidence coming from injury accidents, of which fatal accidents are only a very small proportion (perhaps 2 per cent). Yet what matters most to most people are the fatalities (along with the most serious of the serious injury accidents). There is a tacit assumption that if injury accidents are reduced, fatal accidents will be reduced, also.

In a general way, there is good reason for believing that. However, I have an impression (and I think some others in the road safety world share this) that quite a substantial proportion of fatal road accidents are unusual in some way or other. (As noted in section 2.3, it is possible that the great advances in road safety that have taken place over the last 50 years have reduced the typical crashes by a greater proportion than the unusual ones.) Thus it would be desirable to get a good answer to the question, To what extent, and in what circumstances, does the pattern of non-fatal injury accidents reflect the risk of a fatal accident?

A few points may be made in response to that question. Fatal crashes differ from non-fatal ones in a number of known ways, and interest then lies in the size of the difference (rather than whether it exists). Fatal crashes may differ from non-fatal ones in ways that we do not at present suspect, a possibility of potentially great interest.

Concerning known reasons, I would expect fatal crashes to differ in the following ways.

- Higher speed of the impact of the human.
- Stiffer surfaces impacted by the human.
- Smaller distances between the surface struck by the human and something much more rigid behind it.
- Perhaps, a greater proportion in which injury is caused by an unusual mechanism (e.g., impact of the human with something sharp, crushing, fall from a great height, fire, immersion in water).

- A greater proportion of humans who are frail. To a large extent, with accident data, this refers to being very elderly.

As has been said in sections 16.1 and 16.3, there is interaction between the second and third of these, in the sense that high initial stiffness of a surface can protect the human against excessive deformation that brings something very much more rigid into play. The causes mentioned will lead to some broad types of accident having a greater proportion of fatalities than others: for example, those involving unprotected road users (pedestrians, pedal cyclists, motorcyclists), those occurring at night, and those occurring on high-speed roads.

The list given above refers to what happened to the human. What happened to their vehicle is often a more prominent feature of the accident.

- Higher speed of human impact is likely to be associated with higher travelling speed.
- Stiffer structure struck is likely to be associated with failure to wear seat belt, intrusion (e.g., of a thin rigid pole) into the occupant compartment, and some specifics of vehicle design (e.g., A pillar, rigid metal on large vehicles).
- In many of the cases of injury occurring by an unusual mechanism, the accident itself will be classified as an unusual type.

One of the uses of accident data is to predict where crashes are likely to occur in the future: it is quite likely that crashes will tend to occur at the same places as in the past, and therefore road improvements at these places are more likely to save lives and injuries than at other places. It is not clear to me whether the process of selecting road improvements should consider the likely differences between fatal and non-fatal crashes.

In summary, it seems to me unsatisfactory that, as regards crash location specifically and many other aspects of accidents also, we are unsure about the degree of similarity between fatal and non-fatal accidents.

## **23.6 Accident rates**

The following is based on parts of Hutchinson, Wundersitz, et al. (2009). (See also Wundersitz and Hutchinson, 2008.)

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.

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, Wundersitz, 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 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: Part B 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.

### ***23.7 Induced exposure: A method of by-passing measurement problems***

The following also is based on parts of Hutchinson, Wundersitz, et al. (2009).

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, eliminating 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 14.3.1.) 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.

See Appendix 8 for more on this.

It was noted at the end of section 23.6 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 (Part B of this book) implies that being innocently involved does not equate to being passive and lacking relevant personal characteristics.

## 24. Concluding comments

### 24.1 *Is this book all rubbish?*

A critic may say this book is all rubbish.

- Theory about reaction to emergencies (Part B), they might say, is half wrong and half over-simplified.
- Theory about human impact (Part C), they might say, is half wrong and half over-simplified.
- Calculation of the real-world implications of a test result (Part D), they might say, is much too demanding of data to be practicable.

Suppose all the critic says is correct. Have I wasted my time writing this book, and have you wasted your time reading it? No and no.

- It is reasonable to test AEB systems, and attempt to understand the data. Part B of this book will be a real help to you, whatever mistakes and simplifications there are.
- It is reasonable to test surfaces that may be impacted by humans, and attempt to understand the data. Part C of this book will be a real help to you, whatever mistakes and simplifications there are.
- It is reasonable to wish to get the most out of test results and to assess their implications for a range of conditions that might occur, even if there is not enough data to accurately compute what is suggested. Part D will help you appreciate the several different issues involved.

For the most part, as you see, I will defend the worth of this book. I can, however, sympathise if you expected that the book might spell out what theory means for many particular issues of traffic management policy and practice.

- Unfortunately such an expectation would be overly optimistic. Decisions about specific future road safety interventions should largely be guided by past experience with similar interventions. Theory tends to be too general and abstract.
- But perhaps you say that the empirical evidence is ambiguous and its quality is not very good, and you are keen for guidance from theory? Very likely I would agree with you. But to consider how best to improve road safety practice, and what parts road accident data and road safety theory play, would be a different book.

Although at present theory is not easily or routinely helpful, there will be a few words about this in section 24.3.

## ***24.2 Advantages of theory: Experimental data***

Part B of this book implies that various experiments measuring reaction to emergencies (by a driver or a vehicle acting autonomously) would be well worth doing. Inputs (independent variables) and outputs (dependent variables) are suggested. Models for reaction are suggested that imply specific relationships between the inputs and the outputs.

Part C of this book implies that various experiments measuring impact of an instrumented headform with a deformable surface would be well worth doing. Inputs (independent variables) and outputs (dependent variables) are suggested. Models for deceleration are suggested that imply specific relationships between the inputs and the outputs.

When comparing data and theory, it is very often not clear whether they agree or not --- see the discussion in section 19.16. If they disagree, it is often not clear which is correct and which is wrong. If they agree, it is often not clear whether both are correct or both are wrong. Experimentation is typically difficult, and things go wrong. Useful theories are typically admitted to be simplifications.

I do not see the advantage of theory being (for example) that it is true, or that it is falsifiable. Rather, I think the advantage of theory 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.

We might have (a) a theory for which there is strong evidence, or (more likely) (b) a theory that makes sense and which empirical data does not disprove (albeit with the limitation that existing and likely empirical data are rather poor). I admit there is a wide gulf between these, but even so, I think the second type of theory is often likely to be regarded as good enough.

## ***24.3 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, only a limited number of things affect outcome: travelling speed, how early danger is appreciated, reaction time, strength of deceleration.

- We could concentrate on trying to affect these; we would like to have guidance from theories or data on how to do that.
- If an intervention is not directly aimed at affecting one of those, 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.

And important factors in determining the injury severity (assuming impact of the human does occur) are impact speed, surface stiffness, and deformation distance available before stiffness increases greatly due to bottoming out.

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 2.2.)

The theory given in this book is of wide relevance, but I have also said that there are many crash types that are unusual in one or other respect, and many specialised countermeasures. A great deal of expertise is needed in road authorities --- concerning typical road accidents and the numerous unusual crash types, certainly, but also because of local factors in road design and travel behaviour. And measures to improve road safety do cost money, and expertise is needed in selection to get good value. Even expensive measures may be cheap in comparison with the cost of lives lost, injuries, and damage.

In introducing the potential importance of behavioural proxies for accidents (section 23.4), I drew attention to evaluation and to evaluation being helped by theory. Evaluation, important though it is, is backward-looking. Road safety theory should permit us to be forward-looking, and should help us better select and design road safety interventions. And 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.

As I said in section 1.1, road safety is very much a data-driven subject. But crash numbers are often difficult to interpret. With real-world safety interventions, as with experimentation, theory helps organise, plan, interpret, and understand.

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 (see sections 23.4 and 23.5). But 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.”

My point is certainly not that formal 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.

The road accident problem in developing countries is far, far, worse than it is in Australia. The quality of road accident data is usually worse, also, and it may be that developing countries often need to take action without having much data that can be relied on. 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.

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.

#### ***24.4 Simple messages***

The general line of argument in this book has been that (in many cases) the outcome of a crash depends on what happens in the last second,

which depends on the reactions of a driver who (without necessarily being at fault) is faced with an unexpected obstacle, and these reactions depend to some extent on that person's choices. To me, this seems to mean that everyone --- good drivers as well as bad --- can influence the numbers of people killed and injured.

Obviously, the choices and actions of not-at-fault drivers are choices and actions of *individuals*. Nevertheless, influencing the numbers of casualties is an activity at the *community* level. What I mean is that road transport is very safe, thought of as the average number of injury accidents per journey. The problem comes because road travel is a very frequent activity, and so the total number of deaths and injuries in a community is high (Thorpe, 1967).

- If any of us --- good driver or bad --- resolves to improve their driving, and succeeds, the effect on the problem is minuscule. The success comes when a million of us resolve to improve our driving, and succeed; to "improve our driving" may be as simple as obeying the speed limit.
- And when we are taking collective action (e.g., by passing laws, or setting taxes and fees), we need to be careful to give sufficient weight to safety and risk. Many of those taking action on behalf of the public lack experience of how often or how rarely accidents occur, or how severe or how minor are the consequences. In contrast, they probably do have experience of traffic congestion and of waiting for public transport. They should be careful, therefore, to appreciate what estimates have been made of the consequences for safety and risk of a given action, including appropriate dollar amounts for lives saved or lost, and suffering experienced or avoided.

Some simple messages from Part B.

- Make it possible for a driver, or a vehicle acting autonomously, to react quickly: provide good visibility.
- Make it possible for braking to be strong: provide a high coefficient of friction for tyre-road interaction.
- In a real emergency, the very first braking should be very strong (and, of course, weakened if there is sufficient distance and time).
- Fairly unsophisticated autonomous braking systems are likely to be successful in saving lives.

Some simple messages from Part C.

- A relatively long distance available for deceleration of the human tends to protect against high severity of injury. (A "relatively long distance" may mean 10 cm instead of 5 cm.)
- For a given distance of deceleration, it is probably better for stiffness to be high at first and decrease with increasing deformation. This is to reduce the likelihood of the impact surface bottoming out.

- An impact surface having stiffness that increases with increasing impact velocity is probably desirable for similar reasons.

I believe these suggestions are in line with the thinking of specialists. But, as far as I know, they are not based on formal calculations of the type envisaged in Part D of this book.

Some simple messages from Part D.

- Don't forget the crashes at higher speeds than those you are most concerned with. These cause many of the deaths and serious injuries, even though they are relatively few in number. As an example, a danger of a relatively soft impact surface is that at only slightly higher speeds, bottoming out may occur.
- Don't forget the many crashes at lower speeds than those you are most concerned with. Although these are mostly of low severity, there are so many that the total deaths and total suffering are high.

## 25. Appendix 1: Further results relevant to the effect of mass ratio on injury severity

This continues the discussion of results that began in section 3.4.3. The ratio  $R$  is the ratio of the mass of the lighter vehicle to the mass of the heavier vehicle.

### 25.1 Results

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.

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. As this may be an unfamiliar method, an alternative analysis is given in section 25.2 below.

### 25.2 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 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 3.4.2 and 14.2.)
- In view of the interest in Nilsson's power law (see section 3.2), 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.

### ***25.3 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 3.4.3 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 15 (and especially, for relevant data, section 15.8 and Appendix 4).

## ***25.4 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.

## 26. Appendix 2: Newton's equations of motion

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  $a$ .

$$v = u + a.t$$

$$s = u.t + \frac{1}{2}.a.t^2$$

$$s = \frac{1}{2}.(u + v).t$$

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

$$s = v.t - \frac{1}{2}.a.t^2$$

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

The equation that is most relevant to us is the fourth of these. I will now revert to using the symbols in the same way as elsewhere in this book, not as in the previous paragraph. 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 5.1. Here,  $u$  is the second (lower) speed,  $v$  is the first (higher) speed, and  $a$  is considered positive even though it is a deceleration.

## **27. Appendix 3: Test results of Seiniger and Gail (2015) viewed abstractly**

This continues from section 11.2.4 the discussion of the AEB test results of Seiniger and Gail (2015).

### ***27.1 Explaining performance in testing***

I believe in the usefulness of models, like model [A] and like that of Seiniger and Gail, that attempt to represent what is really happening. However, I would like to consider here the success or failure of an AEB system from the viewpoint of a simple generic model of testing in the abstract. In view of what is said in section 11.2.3, I will here consider only the tests representing adult pedestrians.

What I mean by a simple generic model is one that does not draw on special knowledge of AEB. Instead, it relies on the following general points about testing, tasks, and subjects that attempt the tasks.

- In the present context, there are tasks (to stop before impact), and things (vehicles, or AEB systems) that attempt the tasks.
- The tasks are characterised by one or more parameters describing their difficulty.
- The things are described by one or more parameters describing their ability.
- Performance increases with ability and decreases with difficulty.
- We want a simple description, that is, with as few parameters for difficulty and ability as possible.
- An interesting question is whether ability and difficulty can be defined in such a way that performance of all things on all tasks can be described by the difference between ability and difficulty.

In the tests under discussion, there are at least two types of difficulty: which variant of the test is in use, and the speed.

### ***27.2 Number of parameters needed***

For the dataset under discussion, what is the minimum number of parameters that a model might have?

- *Difficulty resulting from test speed, for low speeds.* In the abstract, one parameter (that is, one measure of difficulty) will be needed for every speed tested. But in this specific context, performance is fully successful up to a maximum speed, and so (for low speeds) one parameter might be sufficient, namely, the maximum speed at which the vehicle stops before impact.

- *Difficulty resulting from test speed, for high speeds.* Speed reduction becomes less at higher speeds. The slope of this decrease is another parameter. (Depending on the details of the model being constructed, the slope might be considered to differ according to variant of test, and/or according to vehicle.)
- *Difficulty resulting from test variant.* The number of parameters will be approximately the number of test variants, three.
- *The vehicle's ability.* The number of parameters will be approximately the number of vehicles (or different AEB systems), four.

### 27.3 *Statement of a generic model*

At this point, the abstract or generic model, lacking any real theory about AEB, can be stated.

- Let  $v$  = test speed, and first consider one vehicle, and one test variant.
- Let  $w$  be the maximum speed for which the vehicle stops before impact. For  $v < w$ , speed reduction =  $v$ . For  $v > w$ , speed reduction =  $w + k.(w - v)$ , where  $-k$  is the slope of the decrease in speed reduction at relatively high speeds.
- For other vehicles,  $w$  is different, but  $k$  is the same. For other test variants,  $w$  is different, but  $k$  is the same.
- For three test formats and four vehicles, there are thus 7 parameters.
- Consider test variant  $i$  and vehicle  $j$ . The model is that at test speed  $v$ , the speed reduction is  $\min\{v, w_{ij} + k.(w_{ij} - v)\}$ . It is supposed that slope  $k$  does not depend on  $i$  or  $j$ , and that  $w_{ij}$  is an additive combination of effects of test variant and vehicle,  $a_i + b_j$ .

### 27.4 *Success of model*

As mentioned in section 11.2.2, Figure 4 of Seiniger and Gail (2015) compares simulation results and test results, there being four cars each tested in three variants of the adult pedestrian test (and one child pedestrian test), and the speeds being between 10 km/h and 60 km/h. What is shown in that Figure are plots of speed reduction versus test speed.

Looking at the plots in Figure 4 of Seiniger and Gail, it seems to me that a model with the very small number of parameters described above would be a good fit to the AEB test data. At a given speed, performance in the test variant labelled CPAN75 is rather better than in CPAN25 or CPAF. And for a given speed and a given variant of test, the third vehicle

(reading from top to bottom of Figure 4 of Seiniger and Gail) is best, followed by the second, the first, and the fourth.

Without using any knowledge of AEB systems or how they are tested, the minimum number of parameters to be expected (based on two types of difficulty and one type of ability) is sufficient.

The point of this is to put into perspective the success of the simulations of Seiniger and Gail. Having said that, I repeat that I believe in the usefulness of attempting to represent in causative models what is really happening.

### ***27.5 Failure of AEB at low speeds***

It was not quite true to say in section 27.2 that performance is fully successful up to a maximum speed. For both the real test results and the simulations, there are some failures at a low speed with success at a higher speed.

- This may simply be random variation in performance.
- It may be a consequence of some sophisticated aspect of the operation of AEB (e.g., avoiding emergency braking when it may not be needed).
- It may be a consequence of the test procedure in which at low speeds the target comes into the vehicle's path only when it is very close (see section 6.2.4).

## **28. Appendix 4: Data on the effect of car mass on injury severity**

This follows on from section 15.8. The data discussed here is mostly from the U.S.A. For further information, see Hutchinson and Anderson (2011, 2013).

### ***28.1 Introduction***

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. British data shows no effect (Grime and Hutchinson, 1979a), but 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.

### ***28.2 Reasons for scepticism***

Three reasons for scepticism about data from the U.S.A. are noted here.

#### **28.2.1 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",

### **28.2.2 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.

### **28.2.3 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.

## **28.3 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)."

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.

## 29. Appendix 5: Improvements in the design of cars for pedestrian impacts

It was mentioned in section 16.2 that Lawrence et al. (2006) demonstrated several methods for improving the pedestrian test performance of specific models of cars. Other papers of that type were also cited in section 16.2. This Appendix is based on part of Hutchinson, Searson, et al. (2011).

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. Several improvements have been noted over the years.

*Beneath the bonnet.* One of the most significant has been the lowering of under-bonnet components, in particular, battery terminals, suspension strut mounts, and engine components. This has been particularly evident in Japanese-manufactured vehicles.

*The side and hinges.* Another significant change that has been noticed is collapsing side guards. In the past, sufficient strength and stiffness of the bonnet and guards to support the weight of people leaning on the vehicle was achieved through thickness of material and rigid support. Using better selection of materials, some manufacturers have reduced the thickness of the panelwork, reducing weight while keeping strength. Attachment of the side guards to stiff reinforced sections of the vehicle is being replaced by the use of supports or brackets that collapse or deform under impact. Typically, attachment of the bonnet to the hinges has been difficult to design safely. Years ago, testing on hinges often resulted in puncturing of the hinge screws through the bonnet top, and extremely high accelerations and HIC have been recorded. Various alternative methods of attachment have been trialled with varying levels of success in lowering HIC and acceleration, but no method is yet considered particularly safe.

*The rear of the bonnet.* Wiper pivots have typically been very injurious. To combat this, some manufacturers have redesigned the wiper pivot on a frangible assembly. A change in design of the firewall has also been noted in various vehicles, where the stiff top section of the firewall that had supported the rear of the bonnet has been lowered or offset rearward to the base of the windscreen. The bonnet has then been supported by a collapsible plastic plenum. Support at the base of the windscreen has and continues to be a notable injurious area. However, a few examples have been seen of this support providing adequate support for the windscreen but yielding when impacted, giving a passable HIC result.

*The bonnet itself.* Its own rigidity and strength requirements can lead the bonnet itself to be injurious, particularly the reinforcement or ribbing and at the extreme front. Some new bonnet designs have seemingly consistent stiffness characteristics across the entire bonnet, the underside reinforced sections having the same impact characteristics as the rest of the bonnet.

## **30. Appendix 6: Behaviours as proxies for accidents**

This continues the discussion of the possible use of behaviours instead of accidents that began in section 23.4. It is based on part of Wundersitz and Hutchinson (2012).

### ***30.1 Introduction***

Wundersitz and Hutchinson (2012) were particularly concerned with the question of whether mass media campaigns can improve road safety. A meta-analysis by Phillips et al. (2011) found an average effect of a 9 per cent reduction in accidents. That is large and valuable, if valid. However, many of the studies included by Phillips et al. were methodologically poor, and the average will not convince sceptics, who will say that the average of many weak studies is still a weak result and the picture remains uncertain. Not very different from the issue of mass media campaigns is that of children's education for road safety, and in this context Gillam and Stevenson (1995) were fairly pessimistic, noting (p. 46) the "difficulties inherent in identifying sound pedestrian education programs, and that "methodological flaws, implausible findings and over-confident interpretations abound".

Wundersitz and Hutchinson 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. 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, fatalities, and injuries directly, but the variability associated with estimates of crash and injury reductions is sufficiently large that both zero effect and a small effect are compatible with the data.

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 at whom the campaign is targeted.

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.

### ***30.2 Laboratory research***

Wundersitz and Hutchinson identified two desirable improvements to the laboratory work.

The first was improved understanding of the relation of the psychological concepts under investigation to safety-related behaviours on the road. Understanding the relation of the psychological concepts to the measurements obtainable would also be necessary. It has been proposed that a mental representation of a risk leads to its cognitive evaluation, emotions then follow and lead to action tendencies --- and people are capable of reporting their action tendencies (Böhm and Pfister, 2000; Xie et al., 2011).

The second was a greater concentration on behaviours rather than feelings in the experiments --- for example, speeds chosen in driving simulators and gap acceptance in virtual environments have already been used (e.g., Algie et al., 2008). Technological improvement in simulated environments are continually taking place, and this area holds some promise.

### ***30.3 Real-world behaviours***

We want to be able to infer safety from behaviour. Consider the three classes of behaviours or observable variables below.

- Examples of behaviours or variables that are closely linked to safety include: blood alcohol concentration (and breath alcohol concentration), speed, and the usage of secondary safety devices (seat belts, child restraints, motorcycle helmets, bicycle helmets). In each case, a change would be seen as implying a change in safety. An important limitation would be that quantitatively it would not be known how much change in safety would result from a given observed behavioural change.
- Further examples of behaviours that are observable are as follows: driver head movements at junctions, pedestrians crossing at designated crossings rather than elsewhere, traffic conflicts, taking a rest break on long journeys, gap acceptance, various driving offences. Wundersitz and Hutchinson considered that in these cases the link with safety is not sufficiently tight that a change in the behaviour would be seen as necessarily implying a change in safety.

- There are scales and questionnaires that purport to measure attitudes and self-reported behaviours. This type of evidence will not usually persuade those who are sceptical about whether mass media campaigns are effective. Firstly, there are substantial measurement difficulties, including limited reliability and validity of these scales. Secondly, the connection between a change in attitudes or self-reported behaviour and crash numbers is insufficiently well established.

### ***30.4 The link between behaviour and safety***

The plausibility of the link between behaviour and safety is vital. It is not clear, however, on what basis plausibility is judged. For the first set of behaviours in section 30.3, the logic is obvious. In the other cases, some form of reasoned theory is highly desirable.

The theory might, for example, involve perception of risk leading to change of behaviour. Brown (2010) reports on a three-observation design in which a media campaign was conducted between Time1 and Time2, and changes from Time1 to Time2 in risk perception were found to be predictive of changes from Time2 to Time3 in self-reported behaviour. Obviously, as Brown concedes, one would ideally also want to strengthen the link between self-reported and objectively observed behaviour.

The more detailed the theory connecting behaviour and safety, the better can its plausibility be judged. Speed is probably the most broadly plausible indicator of danger or safety: reduce speed, and a reduction of crashes is very likely. That argument has some force on its own, but it is improved if details are included about the speed range and circumstances in which a lot of crashes happen. If a countermeasure is shown to reduce speeds in the speed range within which most crashes occur, there can be confidence that the overall risk of crashing is reduced appreciably, but if the effect on speeds is confined to a speed range in which crashes are few, its effect on crashes will be small. Similarly, a reduction of speed among the types of drivers who have most crashes or at the types of site where crashes are most frequent will suggest a worthwhile reduction of the overall risk of crashing, but an effect on safe drivers or at safe sites will suggest only a small effect on crashes.

Archer (2005) concentrates on what are termed proximal safety indicators (very closely related to crashes, e.g., traffic conflicts and measurements related to the conflicts), and also pays some attention to safety-influencing factors (these are less immediately related, e.g., speed). He refers to the events being "representative of the same underlying processes" as crashes, having a "statistical and causal" relationship with crashes, and to a "common causation process" (pp. IX, 42, 46). If objective and widely-accepted criteria existed for deciding whether an indirect

measure can substitute for a count of crashes, Archer would have referred to them; thus the phrases quoted may be taken as evidence that it is unfortunately necessary to rely on common sense, or, if we can spell out details step by step, theory.

Wundersitz and Hutchinson were of the view that the link between behaviour on the road (or performance in the laboratory) and crash occurrence is typically one whose strength, and even existence, is uncertain, and that much more needs to be done to articulate, validate or disprove, and quantify common sense ideas. They suggested that there is likely to be confidence in a theory if it is explicit, with many steps being spelt out, each having been tested and supported.

Better theory is needed in order to link any results from indirect methods (laboratory experiments, and use of behaviours as proxies for crashes) with crashes themselves. Hoekstra and Wegman (2011) made a distinction between rational, automatic, mimicking, and socially conforming behaviours, and this carries a suggestion of theory.

## **31. Appendix 7: Some difficulties with accident rates**

This continues the discussion of accident rates that began in section 23.6. It is based on part of Hutchinson, Wundersitz, et al. (2009).

Whenever something new is found in the crash numbers, exposure is what comes to mind as the likely explanation. That is, a likely reason for some difference being found in respect of the numbers of crashes is that there is some difference in respect of exposure to risk. 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. Very often, it is uncertain whether the main reason is a difference in exposure, or a failure to measure exposure appropriately (e.g., distance travelled might be estimated, but not the number of vehicles encountered), or a difference in risk.

### ***31.1 Risks of different people***

*Individuals.* Some individual drivers have what seems a lot of crashes, over a period of years. But are they genuinely risky drivers, per kilometre driven, or do they have a high exposure? This is typically not known, because there is no data on how far they drive.

*Age/sex groups.* On the positive side, it is quite common for results at a macro scale to be presented. But when more detail is required, difficulties very soon become apparent.

- In the case of young novice drivers, the evolution of crash rates on a scale of weeks (after gaining a licence) is likely to be of interest, but sample sizes in surveys of distances driven have not usually been sufficient to study such questions.
- In the case of elderly car drivers, there may be special problems in gaining honest and correct responses, because of the risk of loss of licence on medical grounds.
- Capturing data on non-motorised modes of transport (e.g., walking and cycling) and on being on the road for purposes other than travel (e.g., recreation, working, playing) are perennial problems.

### ***31.2 Risks at different places***

Are different crash rates associated with different elements of road design? Examples would include street lighting, pedestrian crossings, a centre median (central reservation), sealed vs. unsealed surface, shoulder sealing, the maintenance of the road surface, tidying the footpath to

remove visual obstructions (and camouflage), and so on. And are different crash rates associated with different elements of intersection design? Examples would include gross design (roundabout vs. traffic signal; crossroads vs. offset junctions), skid-resistant surface treatment, phasing of traffic signals (such as the dangers of nonexclusive right turn between oncoming vehicles), cycle time of traffic signals, road markings, and so on. Unfortunately, it is unlikely to be possible to find exposure data that is sufficiently detailed and sufficiently compatible with crash data.

Some measures are directed at reducing exposure to risk without affecting amount of travel, and are not reflected in the usual measures of exposure. (For example, railings prevent pedestrians venturing on to the carriageway for motor traffic, and traffic lights impose a separation in time on conflicting flows.)

Is a specific intersection more dangerous than would be expected? The traffic flows on its several arms may be known, but it is not clear how these should be combined into a summary measure of exposure. But imagine that there exists a body of high quality research establishing that, say, the sum of flows is a better measure than the product of flows. Even in such a case, the research will probably have involved the comparison (perhaps via regression analysis) of numerous different intersections --- and it is not clear that good evidence about a broad-brush generalisation is any sort of evidence at all about what is appropriate for comparing a specific intersection with other intersections.

### ***31.3 Risks of different vehicles***

Are some models of car safer than others? Distances of travel by different models of car are generally not known even at an aggregated level. And it is likely that factors such as nature of ownership (fleet vs. private), age of driver, and circumstances in which they are driven (e.g., urban vs. rural) would have strong effects on crash rates, and these factors might not be independent of model --- with the consequence that differences between models could arise for spurious reasons. Disaggregating distance travelled by different models according to such risk factors is a step or two more difficult than the already difficult task of getting aggregate data for car models.

Consequently, it is often not possible to convincingly study whether crash rates are correlated even with such relatively simple characteristics as size, age of car, year of manufacture, front wheel drive vs. rear wheel drive, sedans vs. four wheel drives, ratio of height of centre of gravity to width of track, or having electronic stability control.

### ***31.4 Other contexts for risks***

A lack of appropriate exposure data is likely to be found also when attempting to determine how dangerous are various environmental conditions (such as times of day, daylight vs. dark, and wet vs. dry), conditions of the driver (alcohol, drugs, fatigue, psychological states such as bad temper or feeling stressed), and behaviours (speeding, following distance, presence of passengers, use of mobile phone).

### ***31.5 Aggregation problems***

Accident rates are typically calculated at a highly aggregated level. It is possible for an aggregation paradox to occur (Wundersitz and Hutchinson, 2008).

- Suppose we want to compare accident rates in conditions A and B, and we have data for several subgroups. (The subgroups might refer to different geographical areas, or different times of the day, or different driver age groups, or other categories.)
- It can happen that accident rate is lower for condition A than for condition B in every subgroup, and yet accident rate is higher for condition A than for condition B when all subgroups are aggregated together.
- This phenomenon will occur when condition A occurs largely in association with subgroups having a high accident rate, and condition B occurs largely in association with subgroups having a low accident rate.

Such a misleading result at the aggregated level is likely to be very uncommon. The possibility is a warning that distortions do occur with aggregated data, and may be quite serious.

### ***31.6 Optimism about the use of accident rates***

Hutchinson, Wundersitz, et al. (2009) also expressed some optimism about the future usage of accident rates. They summed up by listing six reasons why the usefulness of exposure (and risk implied by exposure) may be greater in the future than in the past.

- Availability of technology for tracking people and vehicles.
- Availability of technology for visual recognition (e.g., of vehicle type or number plate).
- Increasing practicability of linking different datasets (e.g., the crash, vehicle registration, and driver licence datasets).
- Random sampling: if a sample is truly random, it does not need to be very big in order to give a good estimate of the population mean. The traffic and transport world has not really embraced the ideas of

deciding what exactly is the population of interest and then taking a random sample. The traffic and transport world could choose to change, and use random sampling more widely.

- Growing awareness of the importance of compatibility between transport and crash datasets.
- The coordinated exploration of crash and exposure datasets with the ideas behind induced exposure (see section 23.7) kept in mind, without premature calculation of risk as the ratio of crashes to exposure, might throw up credible interpretations of why certain crash and exposure numbers co-vary while others do not.

## 32. Appendix 8: Induced exposure

### 32.1 Description

This continues the discussion of induced exposure that began in section 23.7. It is based on part of Hutchinson, Wundersitz, et al. (2009).

It is difficult to determine responsibility for each crash, and for work on large datasets of crashes, some alternative is needed. The following assumptions are an example (Thorpe, 1964).

- (a) Single-vehicle crashes are caused entirely by the driver-vehicle combination concerned. (A driver-vehicle combination means a category such as young drivers in old cars.)
- (b) In each two-vehicle crash, there is a responsible and an innocent party.
- (c) The proportionate involvement of each driver-vehicle combination as the responsible party in two-vehicle crashes is the same as its proportionate involvement among single-vehicle crashes.
- (d) The proportionate involvement of each driver-vehicle combination as the not-at-fault party in two-vehicle crashes is the same as its share of total exposure.

Expressed informally, a dangerous category of drivers or vehicles will show greater over-representation in single-vehicle crashes than in two-vehicle crashes, as there is an innocent party in each two-vehicle crash as well as a responsible party.

As already mentioned in section 23.7, ratios may be calculated using either drivers explicitly judged not to be to blame or using drivers presumed not to be to blame because of the circumstances (e.g., their vehicle was stationary). Both methods can both be found in *Research on Road Safety*, at pp. 118-123 (Road Research Laboratory, 1963).

### 32.2 Criticism

My impression is that induced exposure methods have achieved only modest popularity.

One reason may be that the third of the assumptions above is too restrictive: it seems to imply that there is only one kind of fault, that may lead to either a single-vehicle crash or to (responsibility for) a two-vehicle crash.

That is surely unrealistic. As simple examples, consider driving fast on an empty road and accepting short gaps in a traffic stream. These might or might not stem from a common source, such as poor judgment or a

tolerance of risk. But they are different, and they will have different effects: there might be increased loss-of-control single-vehicle crashes in the first case and increased two-vehicle crashes in the second case, and there is no reason to think these will be of the same magnitude.

### ***32.3 What might the data look like?***

It may be worth considering a specific example, and comparing how the data will look in the case of a category of driver or vehicle or driver-vehicle combination that is much more dangerous than average, and in the case of one that is average. In both cases, suppose it accounts for 1 per cent of single-vehicle crashes. Thus it also accounts for 1 per cent of the at-fault vehicles in two-vehicle crashes.

Consider a category that is much more dangerous than average. Because of this, the number of crashes in which it is involved but not at fault is negligible in comparison with those in which it was at fault. Consequently, this category accounts for about 0.5 per cent of all vehicles in two-vehicle crashes. The ratio of the percentage in single-vehicle crashes to the percentage in two-vehicle crashes is approximately 2.

Now, instead, suppose it is about average. Because of this, the number of crashes in which it is involved but not at fault is approximately the same as the number in which it was at fault. Consequently, this category accounts for about 1 per cent of all vehicles in two-vehicle crashes. The ratio of the percentage in single-vehicle crashes to the percentage in two-vehicle crashes is approximately 1.

That is, because of the set of assumptions (a) - (d) above, the ratio of the percentage in single-vehicle crashes to the percentage in two-vehicle crashes cannot exceed 2. This prediction is sometimes found to fail empirically, possibly due to loss-of-control single-vehicle crashes.

### ***32.4 Discussion***

In the model of (a) - (d) above, half the driver-vehicle combinations have the same pattern as single-vehicle crashes, and half have the same pattern as exposure. The model could be generalised to say that the proportions are not half and half, but  $p$  and  $1 - p$ .

- However, the model would then permit the similarity between single- and two-vehicle crashes to be very low (if  $p$  is low). This would overcome the problem mentioned at the end of section 32.3, as it would be possible for the ratio of the percentage in single-vehicle crashes to the percentage in two-vehicle crashes to be very high.

- Perhaps that is realistic, in view of what has been said about loss-of-control single-vehicle crashes. However, it is very much an obstacle if the aim is to use the pattern of single-vehicle crashes to help predict the pattern of two-vehicle crashes.

It was noted in section 23.6 that reactions of a driver who is not at fault are important in crash occurrence. This is evidently another complicating factor for the induced exposure concept.

I am pessimistic about the prospects for an easy or standardised approach to accident rates or quasi-rates obtained from induced exposure. It is natural to take the ratio of crashes to exposure in order to get a rate, and then see how this is affected by various independent variables. However, as hinted in section 31.6, it may sometimes be better to consider separately the effect of independent variables on crashes and on exposure, and come to an understanding of the totality of effects by that route. Similarly, in view of the difficulties outlined above with regard to induced exposure methods, there is no need to immediately jump to calculation of some ratio of types of crash. Less formal, exploratory, accounts of how single and two-vehicle crashes (and different types of single and two-vehicle crashes) are similarly affected by some variables and differently affected by others might be more fruitful.

### 33. Appendix 9: Stiffness when there are several speeds of impact

Choice of stiffness of a cushion is a complex matter, and I acknowledge that I am only giving one argument.

The example here is a car's bonnet struck by a pedestrian headform. The clearance distance available under the bonnet before bottoming out occurs is presumed to be specified.

At any speed, there is an optimum stiffness of the bonnet. It is approximately the stiffness such that the clearance distance is exactly used up in stopping the headform (see sections 16.1 and 16.3). Increase the stiffness above this, and injury severity increases: the bonnet is unnecessarily stiff for the speed being considered. Decrease the stiffness below the optimum, and injury severity increases sharply: the bonnet is not stiff enough to prevent bottoming out, and this occurs to a greater and greater extent as stiffness decreases.

Optimum stiffness depends on the impact speed. Stiffness corresponding to minimum injury is greater for a high speed of impact than for a lower speed of impact. Chapter 20 gives a method of calculating an estimate of safety performance averaged over the range of speeds that do occur, and section 20.5.1 referred to optimal stiffness over a range of speeds.

Suppose the population of speeds of impact is represented by two speeds of equal frequency of occurrence. For each speed, injury severity depends on stiffness in the way described. Consider injury severity averaged over the two speeds. For what stiffness is average injury severity minimised, that is, what is the optimum stiffness?

I think the optimum stiffness is only a little lower than it is for the higher speed. The reason is the unequal slopes of the two relevant functions. That is, below the stiffness that is optimum for the higher speed, severity at the lower speed decreases with decreasing stiffness, but severity at the higher speed increases sharply with decreasing stiffness because bottoming out is occurring. Consequently, the average increases with decreasing stiffness.

This argument is not rigorous.

- Injury severity needs to mean roughly what it usually means, of course. In addition, the argument relies on injury severity being defined in such a way that averaging is valid. With that restriction, it is not clear that the dependence of injury severity on stiffness

really is much steeper when bottoming out occurs than when it does not.

- For many functions, the lowest point is flat. Thus for the higher speed of impact, the dependence of injury severity on stiffness may be weak in the vicinity of the optimum stiffness. The counter-argument to this is that over the range between the two optimum stiffnesses, there will be a greater change of injury severity in the case of the higher speed of impact (because of bottoming out), and thus the best choice of stiffness is likely to be closer to the optimum for the higher speed than to the optimum for the lower speed.

Nevertheless, I think it likely that it is roughly correct that the optimum stiffness is only a little lower than it is for the higher speed.

The argument can go a step further if we consider what two speeds of equal frequency of occurrence best represent the population of speeds of impact.

- Let *mean* and *s.d.* be the mean and standard deviation of the population of speeds.
- The two speeds *mean + s.d.* and *mean - s.d.* are a suitable choice. This is because if a population of speeds consists of these two speeds in equal proportions, its mean and s.d. are respectively *mean* and *s.d.*

Consequently, the suggestion here is that for a given clearance distance, the optimal stiffness for the variety of speeds of real-world impacts is a little less than the optimal stiffness for speed *mean + s.d.* This argument also is not rigorous.

From a practical point of view, as mentioned in section 16.3, materials with nonlinear stiffness and velocity-dependent stiffness may give further and better design options.

I should warn readers that I think that many people interested in this subject will consider that to be too high a speed and too high a stiffness. As already mentioned, this is a complex subject, and many other arguments might be made. I certainly do not imply that the argument given here is sufficient without considering other arguments. But I do think it quite possible that in choosing stiffness, inadequate weight is sometimes given to bottoming out in high speed impacts.

In principle, optimum stiffness might be estimated using calculations like those in chapter 20. However,  $h(x)$  would need to be known for the range of speeds for which bottoming out does not occur and for the range of speeds for which bottoming out does occur. This is very demanding of data.

Variability of speed has been considered here. Variability of effective head mass could be treated in the same way. Some categories of people

have less mass than others: children, for example. Less mass means less deformation (for given stiffness and given impact speed). Stiffness can be lower before bottoming out occurs.

## **Request**

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

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