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Rune Elvik

Institute of Transport Economics
Norwegian Centre for Transport Research

Towards a general theory of the relationship between exposure and risk

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Summary:

The report is a contribution towards developing a general theory of the relationship between exposure and risk. As a basis for developing such a theory, the concepts of exposure and risk are discussed. It is proposed to define exposure as any event in traffic that has the potential of becoming an accident and places cognitive demands on road users. Events are clearly limited in time and space. Risk is the proportion of events that result in an accident. The basic hypothesis is that there is a negative relationship between the number of events and the risk of accident. Studies illustrating such a relationship are presented. These studies should, however, not be regarded as a stringent test of the basic hypothesis.

Sammendrag:

Rapporten gir bidrag til å utvikle en generelle teori om sammenhengen mellom eksponering og risiko. Som grunnlag for utvikling av en slik teori drøftes begrepene eksponering og risiko. Det foreslås at eksponering kan defineres som enhver hendelse i trafikken som har potensial til å bli en ulykke og som krever kognitive ressurser av trafikantene. Hendelser er klart avgrenset i tid og rom og kan telles. Risiko defineres som andelen av hendelsene som ender med en ulykke. Grunnantakelsen er at det er en negativ sammenheng mellom eksponering og risiko. Studier som illustrerer dette drøftes. Disse studiene kan imidlertid ikke betraktes som en stringent test av grunnantakelsen.

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Preface

This report is intended as a contribution to the development of a general theory of the relationship between exposure and risk. A general theory of this relationship is a theory consisting of hypotheses that specify the shape of the relationship and identify mechanisms that produce the specific relationships.

The report continues research that was first presented in two papers published in Transportation Research Record, one in 2009 and one in 2010. It is proposed to define exposure in terms of specific events that have the potential of becoming an accident. Defining exposure as specific events allows a far more detailed study of exposure than the traditional summary measures of exposure, like vehicle kilometres of travel.

It is highly likely that technological innovations in active safety systems for cars will facilitate the study of road safety based on data about specific events. Cars already have systems that can monitor headway and braking, lane position, skidding (electronic stability control), the presence of vehicles in the blind spot (blind sport cameras) and the presence of pedestrians to activate emergency braking. Most cars also have crash data recorders that can store extensive and detailed data about accidents.

The report has been written by chief research officer Rune Elvik. The report is part of the Strategic research initiative (SIS) road safety, funded by the Norwegian Research Council. Chief research officer Torkel Bjørnskau has been responsible for quality control of the report. Secretary Trude Rømming has prepared the report for electronic publishing. The report is published in electronic form only.

Oslo, June 2014
Institute of Transport Economics

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Summary:

Towards a general theory of the relationship between exposure and risk

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The report proposes a new definition of exposure to the risk of accident in road traffic. Exposure is defined as any event, limited in time and space, that has the potential of becoming an accident and places demands on road user cognition. Events are countable; thus their total number can be regarded as a sampling frame (population) from which accidents are sampled with a certain probability. Risk is defined as the probability of accident, which is simply the number of events of a given type that have an accident as their outcome. These definitions of exposure and risk re-establish the connection between the basic concepts of accident research and probability theory.

This report is a contribution towards a general theory of the relationship between exposure and risk. It is a first attempt to develop the key concepts of such a theory and illustrate some of the insights it can give.

Problems of the conventional use of the concepts of exposure and risk

Historically, the key concepts of accident research, exposure and risk, were derived from the concepts of trials and probability, as defined in the field of probability theory. A trial was any random event that had an accident as one of its outcomes. The probability of an accident was the proportion of trials that had an accident as its outcome. Modern summary measures of exposure, like AADT, annual driving distance or vehicle kilometres of travel, cannot be interpreted as trials in the classic sense of the term. The commonly used indicator of risk, accidents per million units of exposure, cannot be interpreted as a probability and may not even be positively related to it. Thus, as conventionally used today, the concepts of exposure and risk have lost their connection to probability theory. This means that one cannot assume that the product of exposure and risk produces unbiased estimates of the long-term expected number of accidents. In particular, the increasing understanding that risks are non-linear (i.e. depend on the amount of exposure) completely invalidates the use of accident rates to control for the effects of exposure on the number of accidents.

Redefining exposure and risk

This report proposes new definitions of exposure and risk. Exposure is defined as any event, limited in time and space, that has the potential of becoming an accident and places demands on road user cognition. The latter part of this definition, referring to human cognition, is not normally part of the definition of exposure, but has been included because any event producing the potential for an accident is the result of human behaviour and requires action by road users to control it so that it does not become an accident. This may change if fully automated driving becomes a reality.

Events have limited duration and spatial extent. Their beginning and end can be defined precisely enough to allow events to be counted. The total number of events can be regarded as a sampling frame (population) from which accidents are sampled with a certain probability. Risk is thus defined as the proportion of events that have an accident as the outcome.

Events generate a potential for accidents by bringing road users close to each other in time and space, or by requiring the road user to take action to avoid leaving the roadway. The following elementary types of events are proposed:

- Encounters, i.e. vehicles or road users passing each other in opposite directions of travel with no physical barrier to separate them
- Simultaneous arrivals at points where conflicts between road users may arise (junctions, pedestrian crossings)
- Turning movements in junctions (involving road users who did not necessarily arrive at the same time)
- Braking events
- Lane changes on multilane roads
- Overtakings, i.e. one vehicle passing another vehicle travelling in the same direction
- Negotiating horizontal curves

An event typically last a few seconds. For some of the events listed above, their number can be calculated from summary measures of exposure, like AADT. In the future, however, it is likely that motor vehicles will have technology that can recognise the events and be able to count them if technology for this purpose is part of the event-recognising systems. There is already on the market vehicle technology that monitors braking (intelligent cruise control), lane-keeping (related to encounters and running-off-the-road) and blind spots when changing lanes. These systems are probably only the beginning of more comprehensive, integrated systems that can monitor most aspects of traffic. To redefine exposure in terms of specific events is therefore future-oriented and allows for a vastly more detailed study of exposure than current summary measures, like vehicle kilometres. Vehicle kilometres are, essentially, a black box and tell nothing about what happened along any kilometre driven.

Exposure as learning

The repeated experience of a certain type of traffic event will be associated with learning, i. e. road users will become more and more competent in understanding and controlling the events so that they do not result in an accident. In general, therefore, one would expect there to be a negative relationship between exposure and risk. The larger the number of events of a given type, the lower the risk of accident. Hence, even when exposure and risk are redefined as proposed in this report, it will, in general, not be correct to estimate the expected number of accidents by multiplying exposure with risk. By contrast, the non-linearity of the relationship between exposure and risk must be modelled explicitly. The main task in developing a general theory of the relationship between exposure and risk is to propose specific hypotheses regarding the shape of this relationship. Some hypotheses are proposed in this report, but they should be seen only as a first attempt to develop a theory.

Review of empirical studies

Selected empirical studies of the relationship between exposure and risk are reviewed in the report. These studies all support the strong non-linearity of the relationship. One should, however, not regard the review of studies as a test of the hypotheses proposed in a stringent sense of the term. All the studies that have been reviewed are based on summary estimators of exposure, not the event-based concept of exposure proposed in this report. Testing the hypotheses proposed in this report requires data on the number of events of specific types. As noted above, it is likely that such data will be available in the future.

Transportøkonomisk institutt
Stiftelsen Norsk senter for samferdselsforskning

Sammendrag:

Bidrag til en generell teori om sammenhengen mellom eksponering og risiko

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Forfatter: Rune Elvik
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Denne rapporten foreslår nye definisjoner av begrepene eksponering og risiko. Eksponering defineres som enhver hendelse som har potensial til å utvikle seg til en ulykke og krever kognitive ressurser av trafikantene. Hendelser kan telles og det totale antall hendelser i trafikken kan betraktes som en utvalgsramme (populasjon) som ulykkene trekkes fra med en gitt sannsynlighet. Risiko kan defineres som andelen av hendelser av en gitt type som ender med ulykke. Disse definisjonene av eksponering og risiko gjenoppretter forbindelsen mellom grunnleggende begreper i ulykkesstudier og grunnleggende begreper i sannsynlighetsteori.

Denne rapporten er et bidrag til utvikling av en generell teori om sammenhengen mellom eksponering og risiko i trafikken. Rapporten bør tolkes som et første trinn i utviklingen av en slik teori og en illustrasjon av den innsikt teorien kan gi.

Problemer med konvensjonell bruk av begrepene eksponering og risiko

Historisk sett var to av nøkkelbegrepene i ulykkesforskningen, eksponering og risiko, nært knyttet til begrepene forsøk og sannsynlighet i sannsynlighetsteori. Et forsøk var en tilfeldig hendelse der ulykke var ett av de mulige utfallene. Sannsynligheten for en ulykke var andelen av forsøkene som endte med ulykke. I moderne ulykkesforskning bruker man ikke begrepene forsøk eller hendelse, men angir eksponering for risiko med gjennomsnittsmål som ÅDT, årlig kjørelengde eller kjøretøykilometer. Disse eksponeringsmålene er kontinuerlige og kan ikke tolkes som tellbare hendelser. Det vanligste målet på risiko, ulykker per million kjøretøykilometer, kan heller ikke tolkes som et mål på sannsynlighet. Ulykker per million kjøretøykilometer trenger ikke en gang å ha en positiv sammenheng med sannsynligheten for en ulykke. Det er blitt mer og mer klart at antall ulykker ikke nødvendigvis er proporsjonalt med antall kjøretøykilometer. Tvert om ser ulykkesrisiko ofte ut til å være ikke-lineær. Det betyr at man ikke får et forventningsrett anslag på forventet antall ulykker ved å multiplisere kjøretøykilometer med antall ulykker per kjøretøykilometer. Det er følgelig behov for å utvikle et nytt mål på eksponering som gjenoppretter forbindelsen med grunnbegrepene i sannsynlighetsteori.

Nye definisjoner av eksponering og risiko

Denne rapporten foreslår nye definisjoner av begrepene eksponering og risiko. Eksponering defineres som enhver hendelse som har mulighet for å utvikle seg til en ulykke og som krever kognitive ressurser av trafikantene. Siste ledd i denne definisjonen har vanligvis ikke inngått i definisjoner av eksponering, men er tatt med fordi enhver hendelse som kan ende med en ulykke er et resultat av trafikantatferd og krever at trafikantene gir hendelsen oppmerksomhet for å unngå at den ender med ulykke.

Hendelser er klart avgrenset i tid og rom. Det kan defineres når en hendelsen begynte og når den sluttet, slik at hendelser kan telles opp. Det totale antall hendelser av en gitt type i trafikken kan tolkes som en utvalgsramme (populasjon) som ulykker trekkes fra med en viss sannsynlighet. Risiko kan defineres som andelen av hendelser av en gitt type som ender med ulykke. Denne andelen vil vanligvis være meget lav og er ikke nødvendigvis konstant (det vil si uavhengig av antall hendelser).

Hendelser skaper muligheter for ulykker ved at trafikanter kommer nær hverandre i tid og rom, slik at konflikter kan oppstå, eller ved at trafikantene må korrigere kursen for ikke å havne utfor vegen. Følgende grunnleggende hendelsestyper i trafikk er identifisert:

- Møter, det vil si kjøretøy eller trafikanter som passerer hverandre i motsatte retninger uten at det finnes et fysisk skille mellom trafikkretningene
- Samtidige ankomster til mulige konfliktpunkter mellom trafikkstrømmer, for eksempel samtidige ankomster i kryss eller ved gangfelt
- Svingebevegelser i kryss som kan komme i konflikt med andre trafikkstrømmer, selv om kjøretøyene ikke ankommer krysset helt samtidig
- Bremsehendelser, uansett hvorfor noen bremser
- Skifte av kjørefelt, uansett hvorfor noen skifter kjørefelt
- Forbikjøring, uansett grunn
- Kjøring i horisontalkurver

En hendelse vil typisk vare noen få sekunder. En møtesituasjon, for eksempel, er ikke påbegynt når bilene er så langt fra hverandre at en av dem kan krysse over i motsatt kjørefelt så tidlig at den møtende bilen rekker å stoppe eller at den kryssende bilen havner utfor vegen. En møteulykke vil da ikke oppstå. Hendelsen, et møte, starter når bilene er nær nok hverandre til at de ikke vil rekke å stoppe hvis de endrer kurs. Den er slutt når bilene har passert hverandre.

På samme måte kan samtidige ankomster til et kryss for eksempel defineres som ankomst innenfor samme sekund (eller et annet valgt tidsrom). For noen typer hendelser kan man, under visse forutsetninger, beregne antall hendelser hvis man kjenner årsdøgntrafikken (ÅDT). Det er imidlertid mer nærliggende å tenke seg at hendelsene registreres automatisk av kjøretøyet. Nye biler har allerede muligheter for å registrere bremsing (intelligent, eller autonom cruisekontroll), plassering i kjørefeltet (varsel hvis man forlater et kjørefelt), dødvinkel ved skifte av kjørefelt (dødvinkelkamera) eller at man nærmer seg en kryssende fotgjenger i for høy fart til å kunne stoppe. Dette er trolig bare begynnelsen på utviklingen av integrerte tekniske løsninger som kan overvåke bilens omgivelser i alle retninger og registrere hendelser i det området teknologien overvåker. Det er da trolig bare et spørsmål om å utstyre bilen med en lagringsenhet dersom man ikke bare ønsker å registrere hendelsene fortløpende, men også telle dem opp. Å definere eksponering som konkrete hendelser er følgelig fremtidsrettet og muliggjør langt mer detaljerte studier av eksponering enn dagens enkle mål gjør mulig. Kjøretøykilometer er i grunnen bare en svart boks: Vi vet ikke noe som helst om hva som har skjedd den siste kjørte kilometeren og føreren vil ikke kunne fortelle det, fordi kjøringen i høy grad er automatisert og ikke blir lagret i langtidshukommelsen.

Eksponering som læring

Det er naturlig å anta at trafikanter lærer av hendelser de opplever i trafikken. Noen ganger skjer læringen fort, andre ganger må man oppleve en gitt hendelse flere ganger før man kan forutse den og dermed hindre at den utvikler seg i ukontrollert retning. En feil nybegynnere lett kan gjøre, er ikke å undersøke dødvinkelen ved skifte av kjørefelt. En slik feil kan fort ende med ulykke, men vil ofte ende med kraftig tuting fra bilen som ligger i dødvinkelen. Begge deler vil bli opplevd som ubehagelig. Det vil dessuten være åpenbart for føreren hvilken feil han eller hun har gjort. I dette tilfellet kan derfor en eneste feilhandling være nok til at man aldri gjentar feilen.

Andre hendelser kan være vanskeligere å tolke eller lære av. Spesielt kan sammensatte vikesituasjoner (situasjoner der flere trafikanter samtidig har vikeplikt for hverandre) bli løst på mange ulike måter som kan variere fra gang til gang.

Siden trafikantene i det store og hele må antas å lære av hendelser, vil det normalt være en negativ sammenheng mellom antall hendelser og antall ulykker. Enkle hendelser som forekommer ofte gir mange muligheter for å lære. Et møte er en slik hendelse. Man behøver ikke å foreta seg noe annet enn å holde seg i sitt kjørefelt. Men situasjonen krever likevel oppmerksomhet. Selv om man holder seg i eget kjørefelt, er det ikke sikkert at den møtende gjør det. Man må derfor vie situasjonen et minimum av oppmerksomhet. Dette er et eksempel på hva som menes med at hendelser krever kognitive ressurser fra trafikantene.

Hovedoppgaven ved utvikling av en generell teori om sammenhengen mellom eksponering og risiko er å utvikle konkrete hypoteser om formen på sammenhengen mellom eksponering (hendelser) og risiko. Denne rapporten fremsetter noen slike hypoteser, men de kan bare betraktes som en sped begynnelse på en teoriutvikling.

Gjennomgang av empiriske studier

Et utvalg av empiriske studier av sammenhengen mellom eksponering og risiko blir gjennomgått i rapporten. Disse studiene viser uten unntak at det er en sterkt ikke-lineær sammenheng mellom eksponering og risiko. Studiene bør likevel ikke oppfattes som empiriske tester av de hypoteser som fremsettes i rapporten. Alle studiene bygger på summariske eksponeringsmål, ikke de hendelsesbaserte mål på eksponering som foreslås i denne rapporten. Det er, som påpekt over, grunn til å tro at bedre data om hendelser i trafikken vil bli tilgjengelige i fremtiden.

1 The classical model of exposure and risk

1.1 The classical model

The basic concepts of accident statistics were developed by the French mathematician Simeon Denis Poisson more than 175 years ago. Poisson investigated the properties of binomial trials. A binomial trial is an experiment that has two possible outcomes: success or failure. The probability of success is the same at each trial. The outcome of a trial is independent of other trials. Repeated tosses of a coin are an example of a sequence of binomial trials. If a coin is tossed four times, the outcomes can be zero heads, heads once, heads twice, heads three times, or heads all four times. At each trial, the probability of heads (p) is 50 %. When a coin is tossed four times, the probability of getting heads n times (n = 0, 1, …, 4) is:

Heads 0 times:	0.0625
Heads 1 time:	0.2500
Heads 2 times:	0.3750
Heads 3 times:	0.2500
Heads 4 times:	0.0625

The expected number of heads in N trials is N times p. Since p = 0.5, the expected number of heads when N = 4 is 2. Poisson studied what happened to the binomial probability distribution when the number of trials, N, became very large, while at the same time the probability of failure, p, became very low. Denote the expected value in N trials by λ. Poisson found that the probability of x failures in N trials could be adequately described by the following probability function, which bears his name:

$$P\,(X = x) = \frac{\lambda^{x} e^{-\lambda}}{X!} \qquad (1)$$

The parameter lambda (λ) indicates the expected value of the random variable X, x is a specific value of this variable, e is the base of the natural logarithms (e = 2.71828), and X! the number of permutations of x. If, for example, x = 3, then X! = 1 · 2 · 3. If x = 0, then X! = 1. λ = N · p, when N is very large and p is very small. A random variable is a variable that represents the possible outcomes of a chance process. Translating these abstract terms to a language more familiar for road safety researchers gives:

Expected number of accidents (λ) = Exposure (N) · Accident rate (p) (2)

Accident rate is traditionally defined as the number of accidents per unit of exposure:

$$\text{Accident rate} = \frac{Number\ of\ accidents}{Unit\ of\ exposure} \qquad (3)$$

In terms of probability theory exposure ought to refer to the number of trials; accident rate ought to refer to the probability of failure at each trial. In practice, however, the estimators used for exposure and risk in safety analyses do not form independent and homogeneous trials for which risk remains constant independently of the number of trials. This point of view is elaborated in the next section.

1.2 Summary measures of exposure and their weaknesses

There are two problems in using accident rates, as defined above, in order to control for the effects of differences in exposure on the number of accidents. The first problem arises from the fact that accident rate is not independent of exposure, but tends to decline as exposure increases. This tendency is most clearly evident in driver accident rates, as shown in several studies (Massie et al. 1997, Hakamies-Blomqvist et al. 2002, Fontaine 2003, Langford et al. 2006, Alvarez and Fierro 2008). Thus in the study of Hakamies-Blomqvist et al. (2002), accident rates for drivers aged 26-40 years were:

72.4 accidents per million km of driving for drivers whose mean annual driving distance was 1,272 km;

14.7 accidents per million km of driving for drivers whose mean annual driving distance was 8,497 km;

5.8 accidents per million km of driving for drivers whose mean annual driving distance was 25,536 km.

These accident rates cannot be interpreted as estimates of the probability of accidents. The probability of becoming involved in an accident is not even positively related to the accident rates. The mean annual expected number of accidents can be estimated to 0.092 for low-mileage drivers, 0.125 for middle-mileage drivers and 0.148 for high-mileage drivers (estimated by multiplying accident rate by annual mileage). If the assumption is made that accidents occur according to the Poisson probability law, the probability of becoming involved in at least one accident during a year can be estimated to:

0.088 for drivers who drive a mean annual distance of 1,272 km;

0.117 for drivers who drive a mean annual distance of 8,497 km;

0.138 for drivers who drive a mean annual distance of 25,536 km.

In other words: as exposure increases, so does the probability of becoming involved in an accident, but not in proportion to the number of kilometres driven.

The second problem in computing and using accident rates arises in the case of composite exposure, i.e. exposure consisting of two or more traffic movements that both contribute to the risk of accident. Examples include pedestrians crossing the road (both the number of pedestrians and the number of vehicles contribute to the risk) and turning movements conflicting with traffic going straight ahead in junctions. Hauer (2004) illustrates the problem in discussing the effects on safety of providing left turn phases at signalised junctions. The number of accidents involving left-turning vehicles depend both on the number of vehicles turning left and on the number of oncoming vehicles going straight through the junction. Hauer shows by means of an example that if exposure to the risk of a left-turn accident is estimated by using the number of left-turning vehicles to measure exposure, permissive/protected (lagging) phases (i.e. a left turn signal comes on at a time when the opposite traffic stream still has a green signal) have a lower accident rate than protected/permissive (leading) phases (i.e. a left turn signal comes on when the opposite traffic stream still has a red signal but continues into the green phase). If the sum of left-turning and straight-ahead vehicles is used to measure exposure, leading and lagging phases have identical accident rates. If the product of the two traffic movements is used to measure exposure, leading phases have a lower accident rate than lagging phases. The problem is that it is not obvious which of these measures of exposure, if any, that most correctly reflect the opportunity for accidents to occur.

2 Redefining exposure

2.1 Exposure as events

Exposure can be defined as any event that generates an opportunity for an accident to occur. Events form elementary units of exposure, i.e. once identified, events can be counted and their total number determined. Thus, events represent trials in the sense of that term in probability theory. In a previous paper (Elvik, Erke and Christensen 2009) four types of events were defined:

1. Encounters
2. Simultaneous arrivals from conflicting, or potentially conflicting directions of travel
3. Changes of direction of travel close to other vehicles or road users
4. Braking or stopping

It was shown how the number of events can be derived from summary measures of exposure, such as AADT by means of simple mathematical models. Below, examples are given for encounters and simultaneous arrivals (arrivals within the same second) in junctions. For the other types of events, see the paper by Elvik, Erke and Christensen (2009).

Encounters are the passing of vehicles travelling in opposite directions. Each encounter represents an opportunity for a head-on crash on an undivided highway. On divided highways, head-on crashes are still in principle possible, but the opportunities are greatly reduced (Martin and Quincy 2001). The number of encounters on an undivided road equals:

Number of encounters =

$$\left(\frac{Number\ of\ vehicles\ passing\ in\ both\ directions\ per\ unit\ of\ time}{2}\right)^2 \qquad (4)$$

If AADT is known, the number of encounters expected to occur at any point on the road can be estimated for any period of time by dividing AADT by 2, and further dividing by, for example, 24 to obtain mean hourly volume. The number of encounters is obtained by raising the number of vehicles passing a point in both directions, divided by 2, to a power of 2.

The number of encounters increases considerably faster than AADT. If, for example, AADT increases from 1,000 to 10,000 (a factor of 10), the number of encounters increases from 250,000 to 25,000,000 (a factor of 100). This has major implications for the shape of the relationship between exposure and accident rate. According to an accident prediction model (Fridstrøm 1999), the number of multi-vehicle accidents increases in proportion to AADT raised to a power of 1.1 ($AADT^{1.1}$). If the rate of accidents (number of accidents divided by AADT) is plotted as a function of AADT, it will slope upwards. If, on the other hand, the rate of accidents is plotted as a function of the number of encounters (number of accidents divided by number of encounters), which is proportional to $(AADT/2)^2$, it will slope downwards. This is shown in Figure 1 (Elvik 2010).

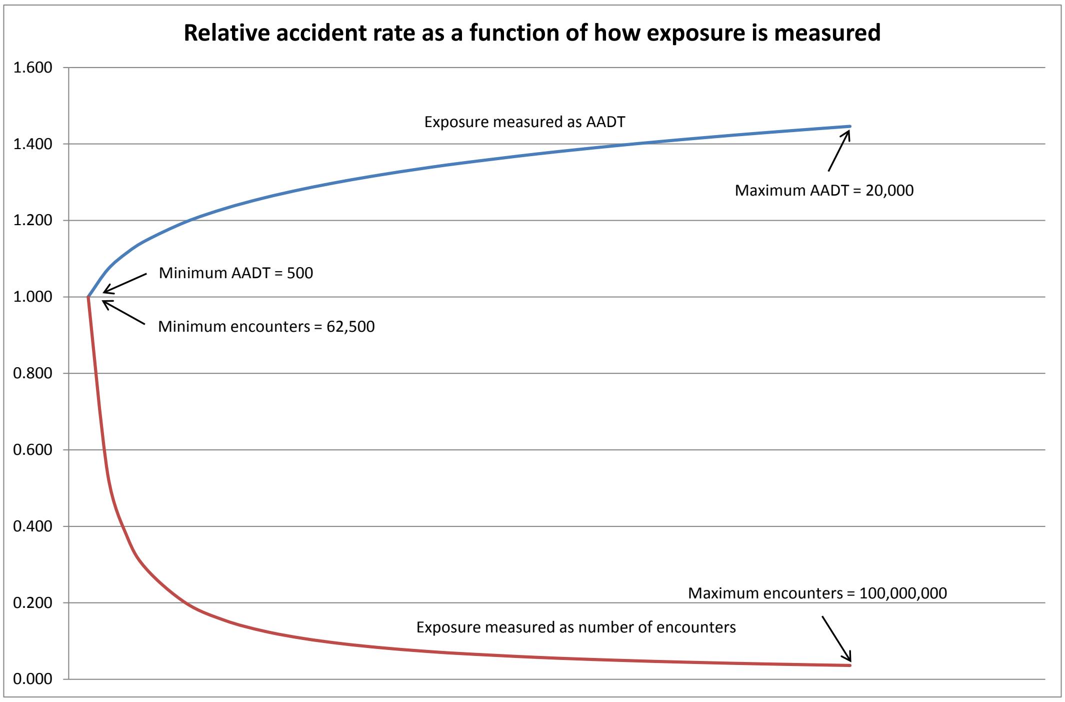

Figure 1: Shape of relationship between exposure and accident rate depending on the definition of exposure

With respect to simultaneous arrivals in junctions, the number of arrivals within the same second also increases considerably faster than AADT. If hourly entering volume from all approaches in a three-leg intersection increases from 200 to 2,000 (a factor of 10), the potential number of conflicts per hour (arrivals from more than one approach within the same 1 second interval) increases from 4 to 298 (a factor of 83). Since the number of events representing a potential conflict increases at a much faster rate than traffic volume, as measured by AADT, the shape of the relationship between the number of events and the number of accidents will be different from the shape of the relationship between AADT and the number of accidents.

2.2 Exposure as learning

When exposure is defined as events, it follows naturally to think about exposure as a process of learning. The shape of the relationship between exposure and risk is therefore influenced by the efficiency of learning that repeated experience of given events provides. The idea that exposure can be regarded as a form of learning is not new. Reason (1997) presents information regarding the probability of making errors when performing tasks with a given description. Table 1 shows the tasks and the estimated error probability for each of them. The probability of error equals the number of times an error was made divided by the number of times the task was performed.

It is seen that the probability of making an error is very high when the task is unfamiliar, but declines to a very low level when a task is familiar and the system supports the operator in performing the task.

Table 1: Probability of making errors when performing certain tasks. Adapted from Reason (1997), Table 7.2

Task description	Error probability
Totally unfamiliar, performed at speed with no idea of likely consequence	0.55
Shift or restore system to a new or original state on a single attempt without supervision or procedures	0.26
Complex task requiring high level of comprehension and skill	0.16
Fairly simple task performed rapidly or given scant attention	0.09
Routine, highly practised, rapid task involving relatively low level of skill	0.02
Restore or shift system to original or new state, following procedures with some checking	0.003
Completely familiar, well designed, highly practised routine task, oft-repeated and performed by well motivated, highly trained individual with time to correct failures but without significant job aids	0.0004
Respond correctly to system when there is an augmented or automated supervisory system providing accurate interpretation of system state	0.0002

Until recently, observing how frequently road users, in particular car drivers, commit errors has been difficult. Naturalistic driving studies now make detailed observation of driver behaviour possible. Although good statistics does not exist, it seems clear that the reliability of human operators in road traffic is very high. Very few of the events that represent an opportunity for an accident result in an accident. In some cases, errors may nevertheless have been made, but there is a margin for error-recovery, giving the road users a chance to correct the error before an accident occurs. Events are opportunities for learning.

It is reasonable to assume that events differ with respect to their potential for learning. In some cases, a single exposure to an unwanted event may be sufficient to prevent its repetition. Thus, a novice driver who neglects to check the blind zone when attempting to change lane, and to his or her great surprise discovers that there is a car in the blind zone, will probably find the experience so unpleasant, and the nature of the mistake so obvious, that it is unlikely to be repeated. This is a case of single-trial learning.

Other events are more subtle and give fewer clues about how to manage them. Judging speed and distance can be difficult and it may not always be clear whether there is time enough to turn left in front of an oncoming car or not. In general, learning from specific events is facilitated if:

1. The event only requires a simple action (the complexity of the event). Simple actions and tasks are easier to learn than more complex actions and tasks.
2. The frequency of the event. Events that occur often give more opportunities for learning than events occurring rarely.

3. The similarity of repeated instances of the event. Events that are completely identical each time are easier to remember and learn than events that differ in some of their characteristics.
4. How quickly an event unfolds. Events that require very fast action are more difficult to manage successfully than those that develop more slowly. The shock and surprise of a very fast event may block effective learning from it.

In addition to these characteristics of events, it is essential to remember that learning is strongly guided by motivation. If it requires too much effort to learn something, if it is experienced as too difficult, motivation is reduced and learning becomes less effective. With respect to road traffic, the concept of motivation can perhaps not be interpreted in exactly the same sense as in learning theory, but the mechanism operating is closely analogous.

There is, up to a certain limit, behavioural adaptation to perceived skill. Thus, a driver who regards himself or herself as highly skilled may decide to drive at a closer distance to the car in front than a driver who has less confidence in his or her capacity to react quickly should the car in front suddenly brake. The limits of behavioural adaptation are, broadly speaking, set by the interaction with other road users and the environment. In dense traffic, you may choose a shorter headway than most other drivers, but you cannot choose a different speed. Likewise, when entering a busy road from a minor road, there are limits to how long you are willing to wait for a gap in traffic while the queue builds behind you. At some point, you just have to dash into the main road, perhaps recognising that the margin is a little tight, but counting on drivers to "let you in" by slightly slowing down. Most of the time, these informal conventions work out fine, but sometimes they break down and an accident occurs.

Adverse environmental conditions also impose limits on behavioural adaptation. In heavy snow at night on an unfamiliar road, a safe driving speed may be, say, 30-40 kilometres per hour. Yet, such a drastic behavioural adaptation is felt as excessive by most drivers. Drivers do slow down, but not enough to maintain safety margins. There is a trade-off between adding travel time and adding to the safety margin. Most drivers probably realise that they are not adapting enough to adverse weather, but prefer to accept a reduced safety margin.

The shape of the relationship between exposure and risk is therefore not determined by learning only, but also by behavioural adaptation. The limits to the shape of the relationship will now be discussed.

2.3 Perfect learning

The example given above of a single-trial learning (a mistake made once is never repeated) may perhaps be seen as an example of perfect learning. In general, however, multiple attempts are needed before you learn something. You have to read a text several times to learn it by heart.

As indicated above, learning can be more or less effective. The more difficult it is to learn something, the less effective learning is likely to be, in the sense that a larger number of repetitions will be needed to reach a sufficient level of skill.

Learning curves of many different shapes can be found in the literature. With respect to traffic exposure as a process of learning, perfect learning will be defined as a hyperbolic risk function, i.e. a hyperbolic curve having exposure (number of events) as abscissa and accident rate per event as ordinate. Figure 2 shows such a curve. The hyperbolic risk function is termed perfect learning because it implies that the expected number of accidents is independent of exposure, i.e. larger exposure will always be perfectly compensated for by a lower accident rate. This is indicated by the numerical example given in Figure 2.

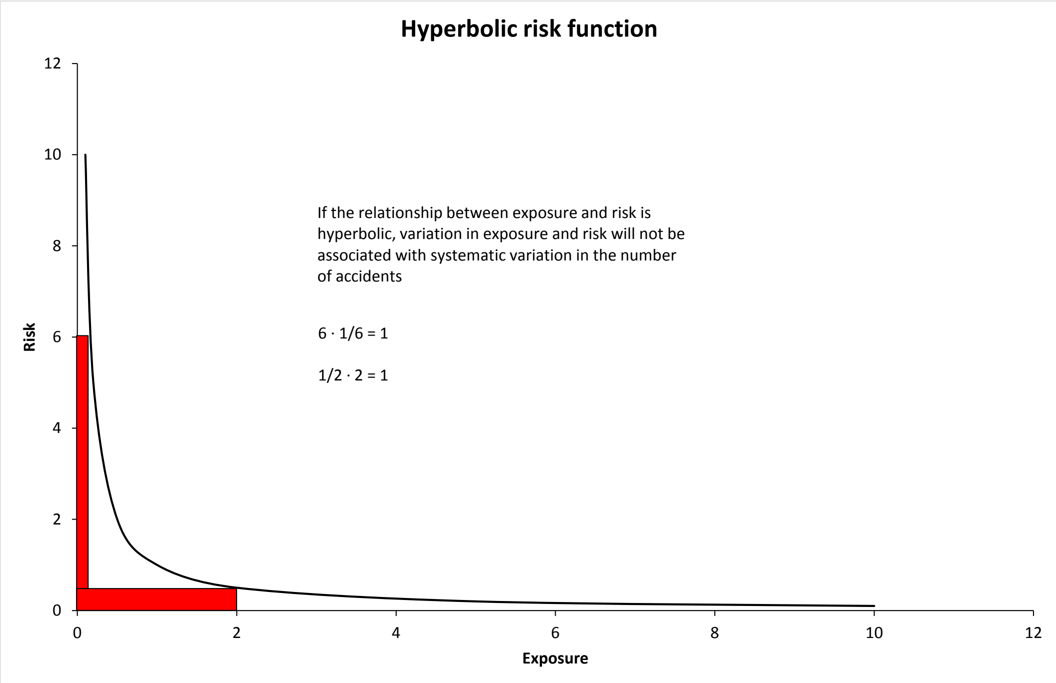

Figure 2: Hyperbolic risk function as perfect learning

Consider a driver who initially was exposed 30,000 events per year with an accident rate of 6 per million exposure events. The expected number of accidents is 0.18 per year. Now suppose that the driver increases his annual exposure to 90,000 events per year, and that this increased exposure was associated with a reduction of accident rate to 2 per million exposure events. The expected number of accidents would still be 0.18 per year.

The hyperbolic risk function has previously been introduced in a different context and given a slightly different interpretation: the law of rare events (Elvik 2006). The idea was that events that are very rare will be associated with a higher level of risk because the events are surprising and drivers will have very limited, or no, experience in dealing with the events.

2.4 Factors influencing the shape of the risk function

Events may differ in a number of respects that influence how easy it is to learn from them. Elvik (2010) discusses three characteristics of events that influence the ease of learning from them.

Events, like encounters or simultaneous arrivals in intersections, are assumed to vary according to three main characteristics: (1) the predictability of the event; (2) the controllability of the event, and (3) the complexity of the event. These characteristics of events are assumed to influence the probability that an event will result in a conflict or an accident and the shape of the risk function – also referred to as the learning curve – showing the efficiency by which road users learn to avoid accidents when involved in specific events. Figure 3 presents a model of how these characteristics of events may interact to determine the level of risk.

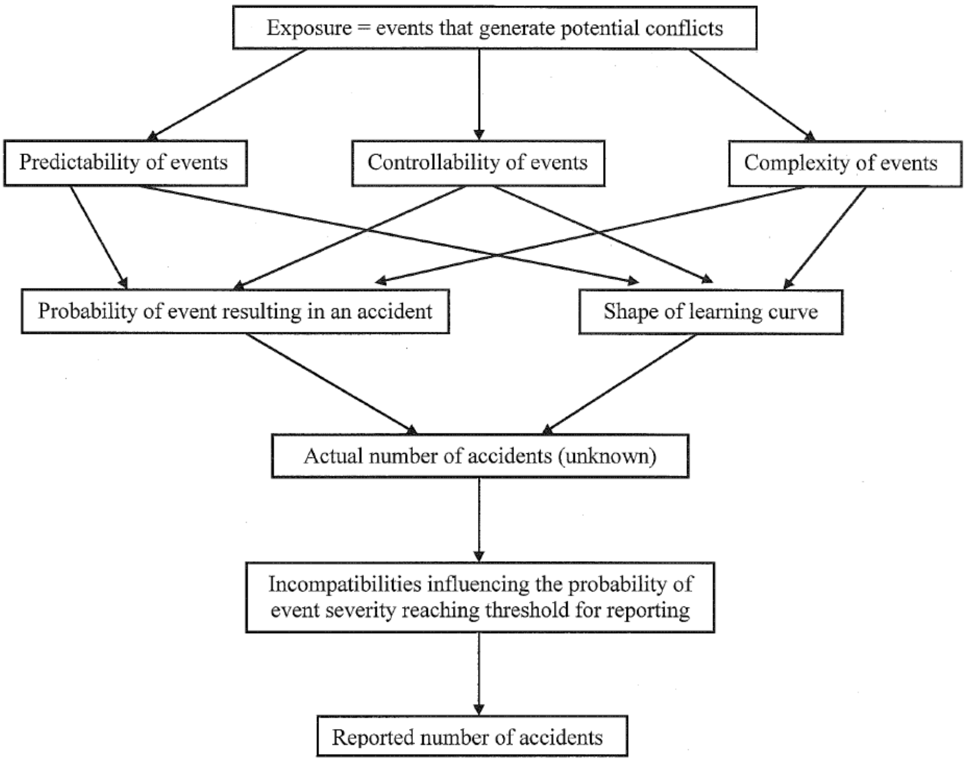

Figure 3: Model of mechanisms by which exposure influences accident rate

The predictability of an event refers to the degree to which road user expectations about the occurrence of the event are correct. An event is predictable if it occurs whenever road users expect it to occur, but never occurs when road users do not expect the event to occur. Predictability is, in other words, the absence of surprises. Predictability in this sense depends on the frequency of an event: frequent events come to be expected, while rare events are not always expected to occur.

The controllability of an event denotes the prospects for bringing an unfolding event under control so that it does not result in a serious conflict or an accident. Controllability depends mainly on how quickly the event develops, but also on how experienced road users are in handling the event, which in turn depends on how often they have been involved in a similar event previously.

The complexity of an event can be defined as the cognitive load it imposes on road users. Turning left onto a major road from a minor road where traffic is controlled by a yield sign can be complex. You need to watch out for traffic from both directions and assess if a gap in the traffic stream is sufficient to enter. Moreover, in urban areas there may also be pedestrians crossing the road to watch out for. Errors resulting in accidents are more likely to be made during events that demand a lot from road users by way of observation, interpretation and decision making than during less demanding events.

Predictability, controllability and complexity interact and influence the probability that an event will result in an accident and the shape of the risk function. The probability of an accident can be defined as any point along the risk function (i.e. the point estimate of risk at that point of the function). Events that are unpredictable, difficult to control and complex will be associated with slower learning, i.e. a flatter risk function than events that are predictable, controllable and simple.

2.5 Estimators of exposure

The most common estimators of exposure in current road safety research are AADT and vehicle kilometres of travel. These are summary measures of exposure, which means that they cannot be interpreted as counts of events or trials that are additive in the sense of probability theory. The summary measures of exposure have no reference to the classical concepts of probability theory that initially formed the basis for accident research (Bortkiewicz 1898).

Another estimator of exposure that has been used in some studies is exposure as a rate or share. This estimator has been used in some studies of the safety-in-numbers effect, i.e. the tendency for the accident rate per pedestrian or cyclist to go down the larger the amount of walking or cycling per inhabitant, or the larger the share of trips made on foot or by bike (Jacobsen 2003). It can be shown (Elvik 2013A) that defining exposure as rate or share can give rise to an artefactual negative relationship between exposure and risk. Figure 4, taken from Elvik (2013A) gives an example of such a relationship.

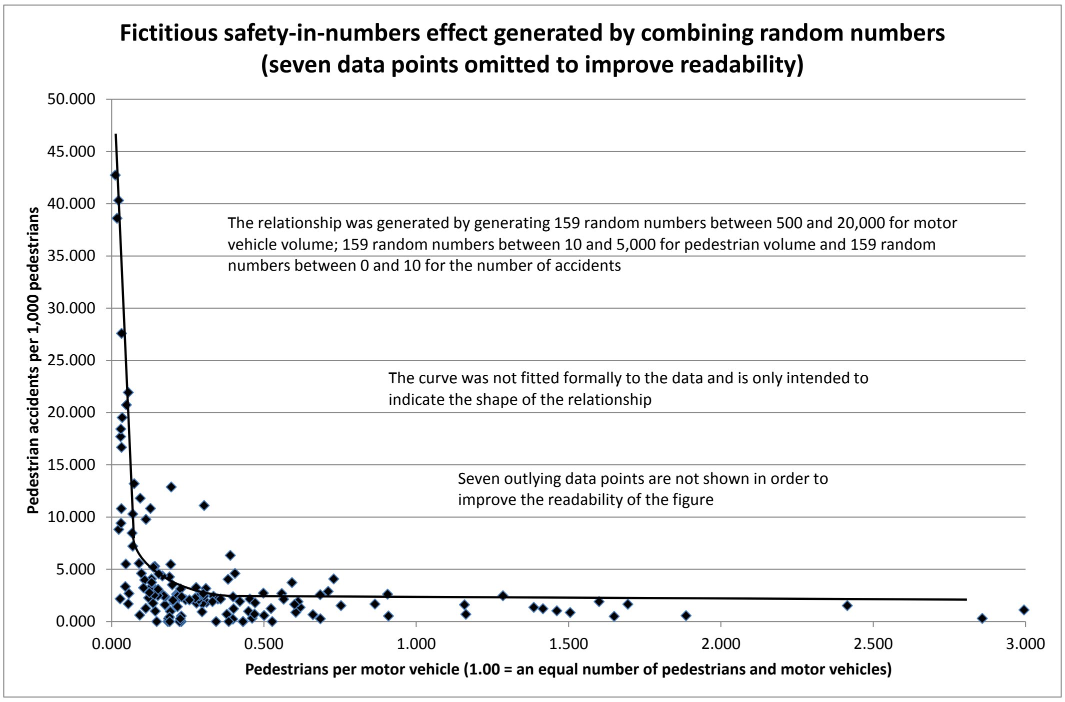

Figure 4: Example of artefactual safety-in-numbers effect for pedestrians

In Figure 4, exposure is measured as the number of pedestrians per motor vehicle (it could equally be the share of trips made on foot). Risk is measured as the number of accidents per 1,000 pedestrians. Thus, exposure is B/C (pedestrians/cars) and risk is A/B (accidents/pedestrians). These definitions may at first blush look unproblematic, since accidents enter only in the definition of risk and cars enter only in the definition of exposure. Nevertheless, these definitions will by necessity generate a negative relationship between exposure and risk. When B increases, A/B becomes smaller, i.e. risk is reduced. At the same time, B/C becomes larger, i.e. exposure increases. Thus, there must be a negative relationship between the variables A/B and B/C. It is a mathematical necessity that follows from the definitions of the variables.

In terms of the theory proposed in this report the best indicator of exposure is therefore the number of events. Events that can be counted and meaningfully regarded as "trials" that have a potential for generating an accident include:

- Simultaneous arrivals at points where travel directions intersect. This includes arrivals at junctions, pedestrians crossings, and railway-highway grade crossings.
- Changes of travel direction that may interfere with other road users. This includes various turning movements in junctions (the vehicles involved in the turning movements need not have arrived simultaneously, but one vehicle may be waiting for a gap in traffic to make a turning manoeuvre) and lane changes on multilane roads.
- Changes in speed requiring action to be taken by other road users. Braking in dense traffic is probably the most common type of event. The number of braking events is countable.
- Encounters between vehicles on undivided roads with two-way traffic. The number of encounters can be calculated by means of a simple formula if AADT is known.
- One vehicle overtaking another vehicle. The number of overtakings can be counted, but not determined a priori, as it depends on driver decisions.
- Negotiating a curve. Horizontal curves have a beginning and an end and passing through them can be viewed as an event. It requires, as a minimum, steering input from the driver, in some cases also speed adaptation. While this is automated behaviour in experienced drivers, it is still fruitful from a theoretical point of view to model it as an event.

Taken together, these events can be logically linked with most road accidents, including:

- Collisions in junctions, involving vehicles going straight ahead or vehicles turning, or combinations of straight-ahead and turning
- Lane-changing collisions
- Rear-end collisions
- Head-on collisions
- Pedestrians hit by motor vehicles
- Cyclists hit by motor vehicles
- Sideswipe collisions during overtaking manoeuvres
- Running off the road in curves

There are some types of accidents that cannot easily be linked with an event-based definition of exposure. These include running off the road on straight road sections and single bicycle accidents. It is a weakness of the event-based concept of exposure that it cannot be logically related to all types of accident. Nevertheless, the fact that countable events, if suitably defined, can be treated as trials the same ways probability theory counts trials, re-establishes the foundation of the concept of road accident risk in probability theory, which offers a deeper understanding of risk and interpretations of risk that can be based on psychology, thus linking these academic disciplines as part of the foundations of road safety studies as an applied field.

2.6 The relationship between estimators of exposure

Can a simple relationship be established between the conventionally applied summary measures of exposure, such as AADT and vehicle kilometres of travel, and the event-based measures of exposure? Previous studies (Elvik, Erke and Christensen 2009, Elvik 2010) have suggested that it is possible to obtain the event-based measures of exposure based on knowledge of a summary measure of exposure.

The links established between summary measures of exposure and event-based measures in previous studies are, however, not complete and rely on certain assumptions, for example that vehicle arrivals at junctions are equally distributed between the various approaches and strictly proportional (i.e. when the number of arrivals in one approach doubles, it doubles in all the others too). Arrivals were further assumed to be random and follow a Poisson-process.

These simplifications were made in order to obtain closed-form solutions permitting the number of events to be estimated if AADT was known. It is clear, however, that the simplifications are somewhat unrealistic. It is nevertheless of interest to get a rough impression of the relationship between summary measures of exposure and event-based measures of exposure.

As far as encounters are concerned, they increase at a much faster rate than AADT. If AADT increases from 2,000 to 4,000, encounters increase from 1 million to 4 million. i.e. by the square of AADT. If the hourly number of incoming in a three leg junction increases from 1,000 to 2,000, the potential number of conflicts (arrivals within the same second) increases from 79.5 to 273.9. This is not quite the square of the increase in the number of incoming vehicles, but close to the square divided by 1.17.

The model developed for braking only assessed the potential for an accident given that a braking event has occurred, not the number of braking events. It seems likely, however, that the number of braking events will increase more than proportional with traffic volume.

With respect to negotiating curves, it involves a heightened risk, i.e. driving in curves has a higher accident rate than driving on a straight road (Elvik 2013B).

Can a relationship between annual distance driven and the number of exposure events a driver will typically experience during one year be established? As an example, consider a driver who drives 13,000 km per year. The median AADT for traffic exposure in Norway (Høye 2014) is about 4,000, i.e. 50 % of vehicle kilometres are driven on roads with a lower AADT and 50 % of vehicle kilometres are driven on roads with a higher AADT.

If traffic is directionally balanced, the oncoming flow will be AADT/2 = 2,000 vehicles. Nearly all of these vehicles will be on the road during daytime; thus mean hourly volume can roughly be estimated as 2,000/16 = 125. Based on the national travel behaviour survey, mean speed is about 45 km/h (Vågane 2011). This may seem surprisingly low, but remember that it includes time spent parking, slow driving in and out of parking spaces, waiting in junctions, and so on. During one year, a driver who drives 13,000 km will spend 13,000/45 ≈ 290 hours in traffic. The total number of encounters will then be 290 · 125 = 36,250.

Based on statistics provided by Høye (2014), the number of junctions entered will be about 9,100 (given the mean number of junctions per km of road). It can further be estimated that in about 20 % of the cases, the driver will need to make a turning movement in a junction. The number of turning movements will then be about 1,820 per year.

The number of situations involving braking is difficult to estimate. If the mean length of a trip is 15 km, an average driver will be making about 860 trips per year. If the guess is made that every trip will involve at least five situations where braking is required, there will be 4,300 braking events that have a potential of becoming an accident each year.

The mean density of curves per km of road implies that a driver driving 13,000 km per year on typical roads will negotiate 26,480 curves with a radius of 300 metres or less per year.

The number of interactions with pedestrians or cyclists is difficult to estimate precisely. Kilometres of travel performed by pedestrians and cyclists amount to about 7.5 % of vehicle kilometres performed by cars (Bjørnskau 2011). As a very crude approximation, the number of interactions with pedestrians or cyclists is set to 7.5 % of the number of encounters, which corresponds to about 2,720 interactions per year.

Summing up these crude estimates gives a total number of events of 77,950 per year for a driver driving 13,000 km. The number of events is likely to increase more than proportional to the number of kilometres driven.

2.7 Hypotheses about the relationship between exposure and risk

Based on the discussion above, the following hypotheses about the relationship between exposure and risks are proposed:

Hypothesis 1:

There is a negative relationship between the amount of exposure (the number of events experienced per unit of time) and the risk of accident (the number of accidents per unit of exposure).

This is a general hypothesis. It describes a statistical regularity. It is, as such, similar to other relationships in accident research and exceptions from the relationship cannot be ruled out. However, in the normal case, the relationship between exposure and risk is negative.

Hypothesis 2:

Frequent events are associated with more effective learning than events occurring less often. More effective learning is evidenced in a more strongly negative relationship between exposure and risk than less effective learning.

Perhaps the most frequent event of all those listed above is an encounter. It is also a very simple event. It does not require any particular action from the driver, except for staying within his or her driving lane. Learning how to avoid head-on collisions when encountering a motor vehicle should therefore be very simple and the efficiently of learning should be high; i.e. repeated events should be associated with a sharply decline risk per event.

Hypothesis 3:

Complex events are associated with less effective learning than simple events. A complex event is one that is cognitively demanding, by requiring the attention to several information elements at the same time, combined with judging speed and distance and having to be performed within a short time.

An example of a complex event is turning left into a main road in a four leg junction from a minor road with yield signs. In this situation, the driver entering the main road must give way to:

- Traffic straight ahead from the left on the main road
- Traffic straight ahead from the right on the main road
- Traffic turning left into the minor road from the main road
- Traffic going straight ahead from the opposite approach of the minor road
- Pedestrians crossing the minor road
- Pedestrians crossing the major road

A driver must pay attention to all these traffic movements at the same time and look for gaps in traffic that are sufficient to enter the main road. It is likely that the traffic situation will differ from time to time – sometimes there will be very little traffic, making the task easy, at other times there may be dense traffic, making the task very demanding.

Hypotheses 4:

Events that have significant duration and/or require major behavioural adaptation to maintain a low level of risk, will be associated with less effective learning than events not lasting long or not requiring major behavioural adaptation.

It may be to stretch concepts to refer to more long-lasting events as events. An encounter lasts a few seconds or less, turning left in a junction may last a few seconds, waiting for a pedestrian to cross the road may also take a few seconds. Most of the events that constitute exposure as defined in this report last only a few seconds at the maximum. Adverse weather, on the other hand, may last for hours.

It is an event that makes driving more demanding and difficult, but drivers do not fully adapt their behaviour to adverse weather or slippery roads. This is not a matter of not learning, but of deliberately trading off safety against mobility and accepting a somewhat higher level of risk which, on the other hand, costs less in terms of increased travel time than fully adapting to difficult driving conditions.

The next chapter presents selected studies shedding light on the hypotheses and showing how they can be tested empirically.

3 Empirical studies of the relationship between exposure and risk

3.1 Driver accident rates and annual driving distance

Several studies have noted a negative relationship between the annual distance driven and driver accident rate (Hakamies-Blomqvist et al. 2002, Fontaine 2003, Langford et al. 2006, Alvarez and Fierro 2008). Figure 5 is based on these four studies and combines their results. Since the absolute accident rates are not likely to be comparable, they have been converted to relative accident rates. In each study, the accident rate for drivers with the longest annual driving distance was set equal to 1. In all studies, drivers were divided into three groups with respect to annual driving distance:

1. Short, which is less than 3,000 km per year. The typical mean distance of drivers in this group is around 1,500 km per year.
2. Medium, which is between 3,000 and 14,000 km per year. A typical mean in this group is around 8,000 km per year.
3. Long, which is more than 14,000 km per year. A typical mean in this group is around 22,000 km per year.

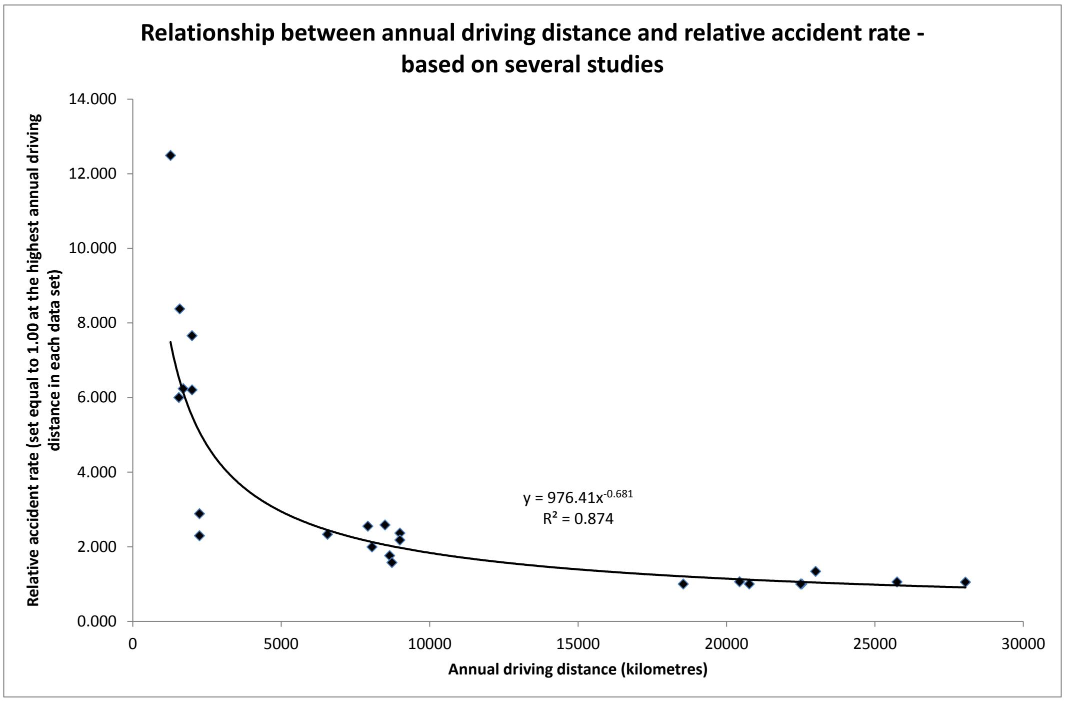

Figure 5: Relationship between annual driving distance and accident rate. Combined findings of four studies (see text)

There is a clear negative relationship between driving distance and accident rate. A power function best fits the data and indicates a risk elasticity of -0.681. Drivers with the shortest annual driving distance have an accident rate which is up to 10 times higher than drivers with the longest annual driving distance. The samples studied included both middle-aged drivers and older drivers. The tendency for accident rate to decline as driving distance increases therefore appears to be general. It applies to all drivers, not just to novice drivers (Sagberg 1998) for whom a risk curve like the one shown in Figure 5 could reasonably be interpreted as a learning curve. Apparently, the learning curve interpretation is not altogether unsupported even for more experienced drivers.

It should be added, however, that kilometres driven per year, like all summary estimators of exposure is imprecise and likely to be confounded. Thus, it is known that older drivers tend to restrict their driving to easier situations, such as driving only in daytime, in light traffic and on familiar roads. Such a behavioural adaptation would tend to reduce their accident rate independently of the number of kilometres driven per year.

Modern techniques for data collection, including naturalistic driving studies, make it possible to collect very detailed data on driver exposure. One study based on such data will be reviewed in the discussion section of the report (chapter 4).

3.2 Encounters – a case of nearly perfect learning

An encounter is a very simple interaction between two road users. It does not require any action on their part, except for staying in their own driving lanes. Yet, head-on collisions are a major road safety problem, making, at least in Norway, a greater contribution to traffic fatalities than any other type of accident (Statens vegvesen et al. 2014).

A comprehensive study of factors contributing to road accidents (Fridstrøm 1999) suggests that multi-vehicle accidents increase slightly more than proportional to vehicle kilometres of driving. However, when the rate of accidents is stated per encounter, it drops dramatically as the number of encounters increases, see Figure 1 (page 5).

In Chapter 2, perfect learning from events was defined as a hyperbolic risk function, in which the risk of an accident is halved whenever the number of events is doubled. Thus, 100 events with a risk of 0.5 per event will be associated with 50 mishaps. If there are 200 events, risk per event is halved to 0.25 and there will again be 50 mishaps, and so on. The reason for referring to such a relationship as perfect learning is that the increased reliability of performance associated with an increasing number of repetitions will prevent the number of mishaps from increasing; thus, the number of accidents will be independent of exposure – it will be the same for 100 events as for 500 events or 50,000 events.

This, obviously, is a limiting condition not likely to be observed in practice. One may, however, use the hyperbolic risk function as a reference for developing an estimator of the efficiency of learning. Perfect learning is represented by the hyperbolic risk function; actual learning is represented by the actual risk function, having the number of events as its argument (abscissa) and relative risk as the outcome (ordinate). The ratio of actual learning to perfect learning is an estimator of the efficiency of learning.

To illustrate these notions, suppose that the number of head-on collisions is proportional to $AADT^{1.1}$ as estimated by Fridstrøm (1999). The number of head-on collisions will increase more than proportional to traffic volume, and accident rate, as conventionally estimated, will increase as traffic volume increases. The expected number of head-on collisions has been estimated for AADT values ranging from 100 to 20,000. At an AADT of 100, the number of encounters will be $(100/2)^2 = 2{,}500$. At an AADT of 200, it will be 10,000.

If the number of head-on collisions expected to occur at the lowest AADT is set equal to 1, the relative rate of head-on collisions per encounter will decrease. At AADT 200, the relative rate of head-on collisions per encounter (2,500 encounters at AADT 100; 10,000 encounters at AADT 200) will be 0.536 according to the accident prediction model ($AADT^{1.1}$), but 0.25 according to the perfect learning curve, since the number of encounters is four times greater. The ratio of actual risk reduction (1 – 0.536 = 0.464) to the risk reduction implied by perfect learning (1 – 0.25 = 0.75) is the estimator of the efficient of learning: 0.464/0.750 = 0.619. Figure 6 shows how the efficiency of learning depends on the number of encounters.

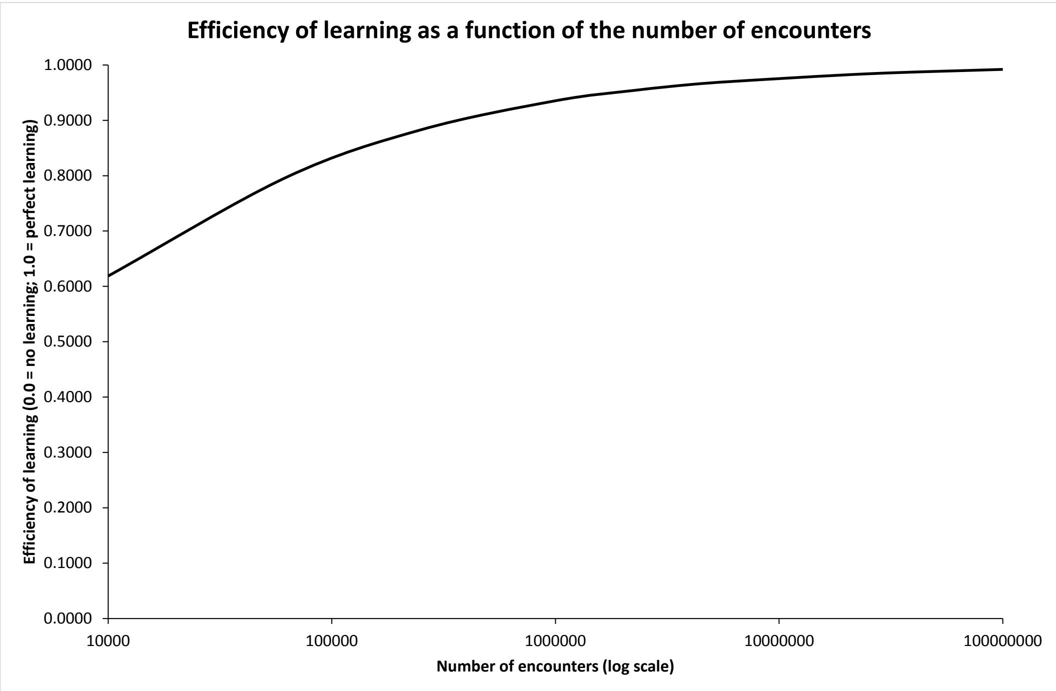

Figure 6: Efficiency of learning as a function of the number of encounters

It is seen that the efficiency of learning goes asymptotically to 1 as the number of encounters goes to infinity. This shows that an increased number of repetitions is associated with more reliable performance. Another mechanism likely to be operating here is the influence of traffic density on driver alertness. On roads with a dense traffic flow, the driver is constantly reminded of the presence of oncoming vehicles and pays attention to them more or less automatically.

3.3 The frequency of adverse weather

It has been noted that accident rates in adverse weather and on slippery road surfaces depend on their frequency of occurrence. A fairly sophisticated study of the effects of weather on accident rate was presented by Eisenberg (2004). Eisenberg developed a set of negative binomial regression models relating weather variables to accident counts, while controlling for traffic volume. A sample of results are shown in Figure 7.

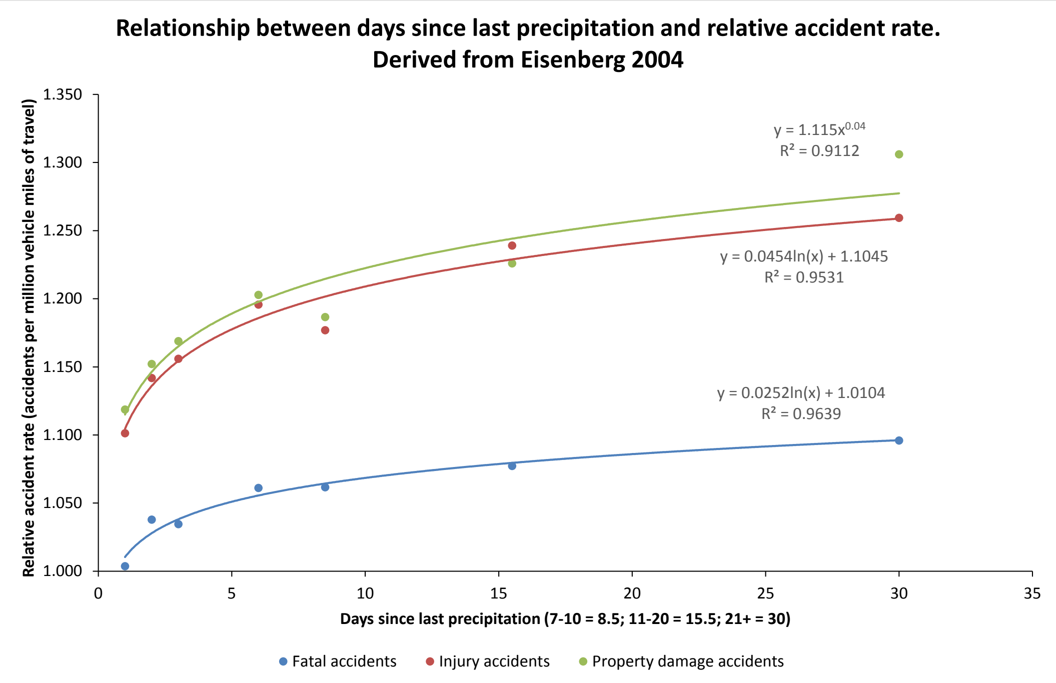

Figure 7: Relationship between days since last precipitation and relative accident rate. Derived from Eisenberg 2004, Table 8

It is seen that when many days have passed since last precipitation, drivers appear to be less prepared for it than when few days have passed. Accident rate therefore increases more when a long time has passed since last precipitation than when only a short time has passed. Furthermore, it is seen that the rate of property damage accidents increase more than the rate of injury accidents, which in turn increases more than the rate of fatal accidents. Thus indicates that drivers adapt behaviour to adverse weather. Accidents therefore become less serious, but behavioural adaptation is not sufficient to prevent accident rate from increasing.

A well-known case of a negative relationship between exposure and accident rate is the relationship documented in Sweden between the share of driving taking place on roads covered by snow or ice and the relative accident rate on such road surfaces. Figure 8 shows this relationship, based on information given by Niska (2006).

It is seen that as the share of driving on snow or ice increases, accident rate goes down. Unfortunately, the relationship shown in Figure 8 may be artefactual, since risk is defined as SI/D (snow/ice divided by dry road) and exposure as SI/T (snow or ice as share of total).

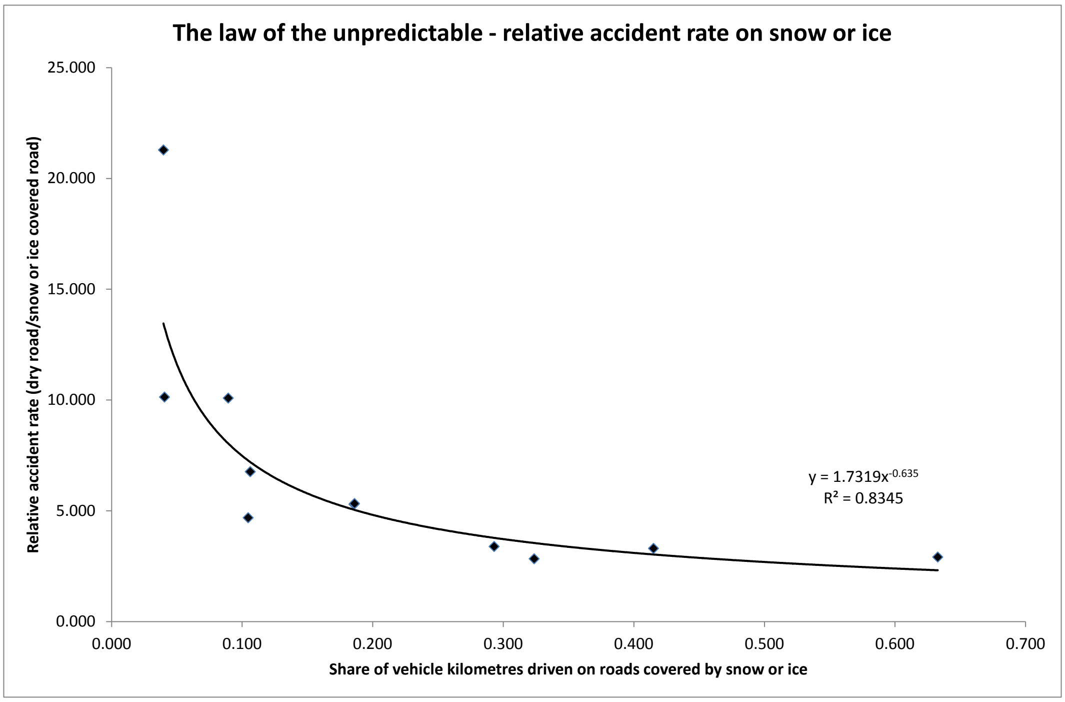

Figure 8: Relationship between relative accident rate and share of traffic on snow- or ice-covered roads. Source: Niska 2006

As defined in Figure 8, there must be a negative relationship between the variables. A real test of whether there is a negative relationship between exposure and risk must be based on definitions of exposure and risk that are logically independent of another (i.e. the definition of one of the concepts must not contain terms common to the definition of the other concept). Figure 9 shows the relationship based on valid definitions of the variables.

In Figure 9, it is not a logical or mathematical necessity that the variables must be negatively related to each other. In terms of the definition of the variables, Figure 9 is identical to Figure 5 (page 15) regarding driver accident rates. There is still a negative relationship, but not as strong as the one shown in Figure 8. There is therefore evidence that driving more on snow- or ice-covered roads (in terms of the absolute number of kilometres driven; not their share of the total kilometres driven) is associated with a reduced accident rate. It is reasonable to interpret this as an effect of learning.

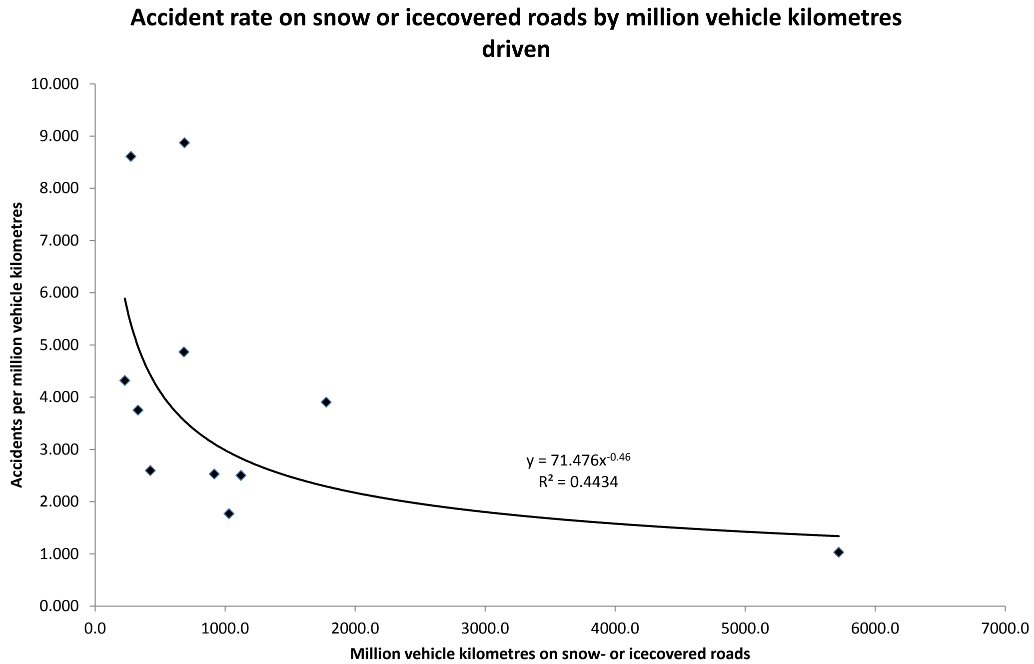

Figure 9: Accident rate on snow or ice-covered roads and kilometres driven on such roads. Based on Niska 2006

3.4 Safety-in-numbers

Safety-in-numbers refers to the tendency for the accident rate of a certain group of road users to go down as the group becomes more numerous. The existence of such an effect is best determined by developing accident prediction models of the form (Elvik 2013A):

Expected number of accidents = = $e^{\beta_0}(PED)^{\beta_1}(MV)^{\beta_2}e^{(\sum_{i=1}^{n}\beta_i x_i)}$ (5)

PED (alternatively CYC) denotes pedestrian (or cyclist) volume, MV denotes motor vehicle volume (usually in terms of AADT = Annual Average Daily Traffic), e is the exponential function, X_i (i = 1 to n) represents risk factors influencing safety, e.g. the mean speed of traffic, the number of travel lanes, the number of legs in junctions, etc. and β_i are coefficients which are normally estimated by means of negative binomial regression. If the coefficients referring to traffic volume (β_1 and β_2) are less than one, this indicates the presence of a safety-in-numbers effect.

Several studies testing for the presence of a safety in numbers effect have been presented in the literature. A systematic review and meta-analysis of these studies is presented by Elvik and Bjørnskau (2014). According to a random-effects model of meta-analysis, which allows for systematic variation in coefficient estimates between studies, the weighted mean values of the coefficients are 0.53 for motor vehicle volume, 0.43 for cycle volume and 0.51 for pedestrian volume.

Applying these coefficients, Figure 10 shows how accident rate (accidents per road user) depend on the number of road users of a given category (motor vehicles, pedestrians, cyclists). It is seen that the curves track each other closely and have the same shape. The minor differences in coefficients are thus unimportant.

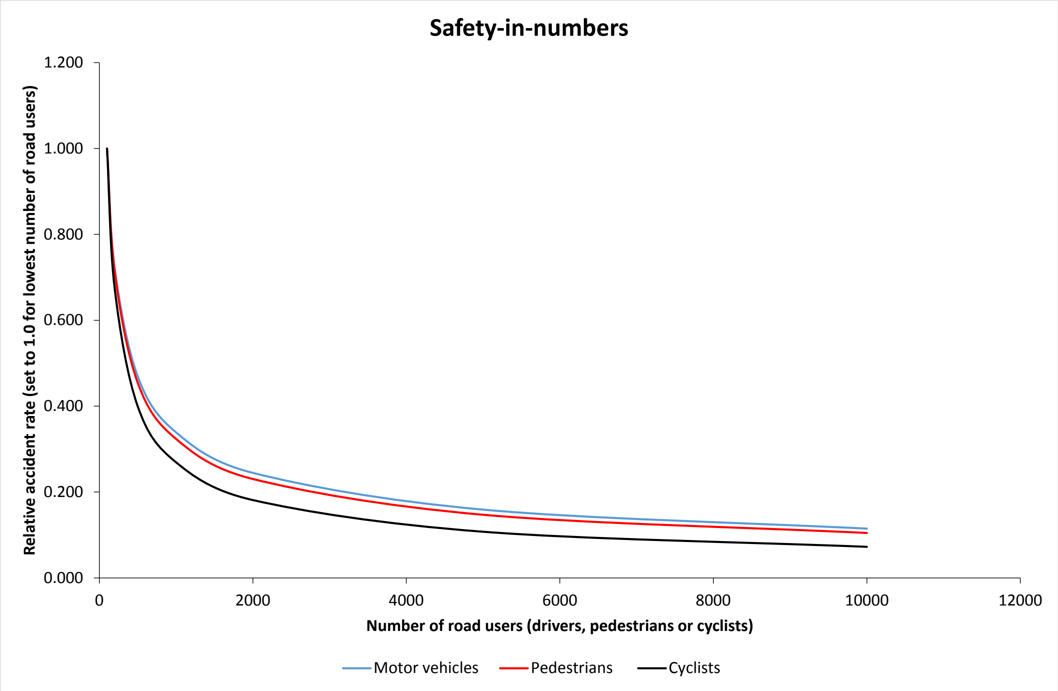

Figure 10: Safety-in-numbers. Based on Elvik and Bjørnskau 2014

Roughly speaking all coefficients are about 0.5. An exponent of 0.5 is the same as a square root transformation of a variable. This implies that a doubling of traffic volume will be associated with a 41 % increase in the expected number of accidents, since the square root of 2 equals about 1.41.

3.5 Safety-in-loneliness

Vanlaar (2008) presents an interesting study shedding light on a phenomenon which, in a sense, is the opposite of safety-in-numbers. It might perhaps be labelled safety-in-loneliness. It refers to the route choices made by drinking drivers.

Based on extensive roadside surveys conducted in British Columbia, Canada and in Belgium, Vanlaar develops a logit model to estimate the probability of identifying a drinking driver as a function of hourly traffic volume and a number of other variables. Figure 11 shows the results.

For Belgium, the estimated percentage (model-estimate) of drunk drivers at an hourly volume of 20 was 0.819. For a volume of 1,500 vehicles per hour, the corresponding estimate was 0.043 %. A similar tendency was found in British Columbia, but the overall level of drinking and driving in British Columbia was lower than in Belgium. The curves presented in Figure 11 imply that there, in absolute numbers, will be fewer drinking drivers on roads with an hourly volume of 1,500 than on roads with hourly volumes of 100, 500 or 1,000.

This makes sense from the perspective of the drinking drivers. They are probably correct in assuming that on low-volume roads, the police are less likely to do any enforcement than on high-volume roads. Moreover, there are fewer other road users who may witness the drinking drivers and possibly report them to the police. Finally, the driving task is easier, because there are fewer cars the drinking driver may crash with.

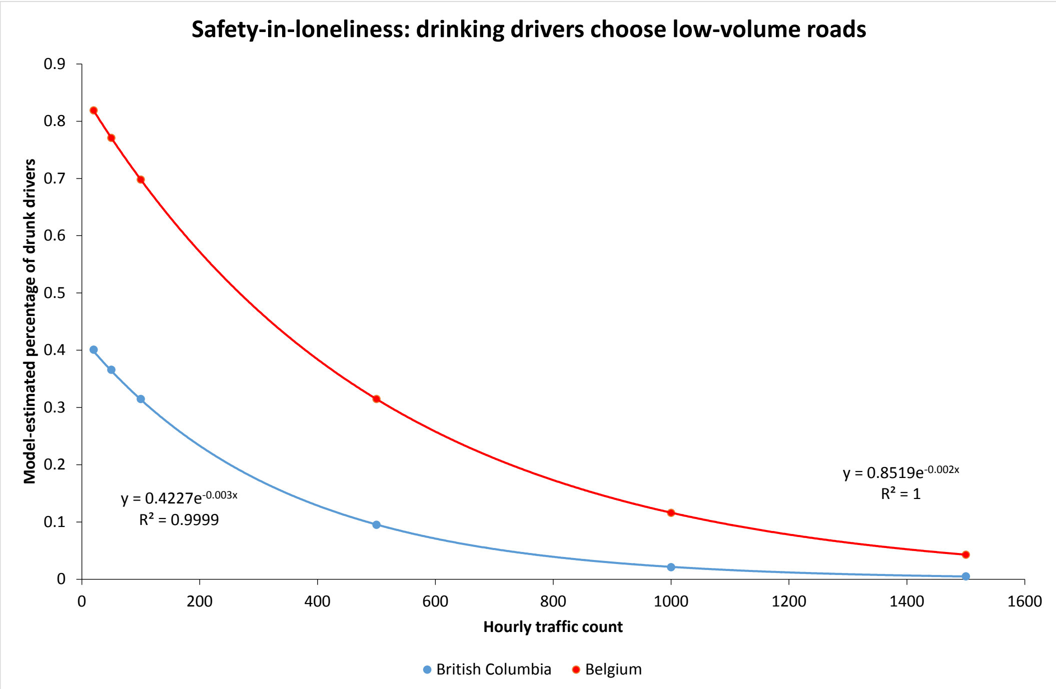

Figure 11: Safety-in-loneliness: drinking drivers choose low-volume roads. Based on Vanlaar 2008, Table 4

On the whole, therefore, the pattern revealed by Vanlaar attests to the high degree of rationality of the choices made by drinking drivers.

3.6 Complexity and the efficiency of learning

It was suggested in Chapter 2 that the complexity of traffic events is one of the factors that influences how well road users learn to deal with the events. The more difficult it is to deal with a traffic event, the more difficult it is to learn from the event.

Three-leg junctions and four-leg junctions differ greatly with respect to their potential for generating complex traffic situations. There are nine potential conflict points between the traffic movements in a three-leg junction; thirty-two potential conflict points between the traffic movements in a four-leg junction. All else equal, four-leg junctions will produce many more complex traffic situations than three-leg junctions.

To test whether the efficiency of learning from potential conflicts is greater in three-leg junctions than in four-leg junctions, a set of 732 junctions for which a number of accident prediction models have been developed was used (Elvik 2013C). The best fitting model (i.e. the model with the smallest over-dispersion parameter) was selected. Based on the predictions of this model, empirical Bayes estimates of the long-term expected number of accidents were developed for each junction. The empirical Bayes estimates are a weighted average of the recorded number of accidents in each junction (which in the majority of junctions was zero) and the model-predicted number.

The potential number of conflicts in each junction was estimated by applying the closed-form expressions given in Elvik, Erke and Christensen (2009). The estimates developed by these formulas are only approximately correct, as they are based on an assumption that all approaches to a junction have the same traffic volume (i.e. 1/3, 1/3 and 1/3 in three-leg junctions and ¼, ¼, ¼ and ¼ in four-leg junctions. This is almost never the case in practice, but it maximises the number of potential conflicts. If entering volumes are unbalanced, the probability of simultaneous arrivals is smaller than if entering volumes are balanced.

Risk was estimated as the empirical Bayes estimate of the number of accidents divided by the potential number of conflicts. This estimator indicates how successful road users are in managing the conflicts so that they do not develop into accidents. The higher the risk, the less the success. Risk was, unsurprisingly, negatively related to the potential number of conflicts. The higher the potential number of conflicts, the lower the risk. This indicates that road users learn from conflicts and become better at preventing them from becoming accidents the more conflicts they are exposed to.

In keeping with the definition of perfect learning, the risk associated with perfect learning was defined as the inverse value of the potential number of conflicts. In other words, if the potential number of conflicts increases from 1 to 4, risk is reduced from 1 to 0.25. The actual risk function was then compared to the hyperbolic risk function and the efficiency of learning determined. The closer the actual risk function is to the hyperbolic curve, the higher the efficiency of learning.

The junctions were divided into groups based on the number of legs (3 or 4) and speed limit (50, 60, 70, 80 or 90 km/h). Three-leg junctions with a speed limit of 50 km/h were assumed to represent the easiest situation. There are few conflict points, and the low speed limit will give road users more time to understand and solve the conflicts than higher speed limits. At the other end, four-leg junctions with a speed limit of 80 km/h were assumed to represent a more demanding situation. There were too few junctions with a speed limit of 90 km/h to use in the analysis.

If complexity makes effective learning more difficult, one would expect the efficiency of learning to be lower in the high-speed four leg junctions than in the low-speed three-leg junctions. Figure 12 shows that this is indeed the case. The blue dots represent three-leg junctions with a speed limit of 50 km/h, the red dots represent four-leg junctions with a speed limit of 80 km/h. The greater efficiency of learning in the three-leg junctions is apparent from two facts:

1. The curve fitted to the data points is steeper than the curve fitted to the data points for four-leg junctions.
2. At a high potential number of conflicts, the data points are closer to perfect learning in three-leg junctions than in four-leg junctions.

The complexity of traffic events is therefore one of the characteristics that influences how much, and how well, road users learn from the events. While the risk of accidents associated with simple events fall very sharply as a function of the number of events, the risk function associated with more complex events is flatter.

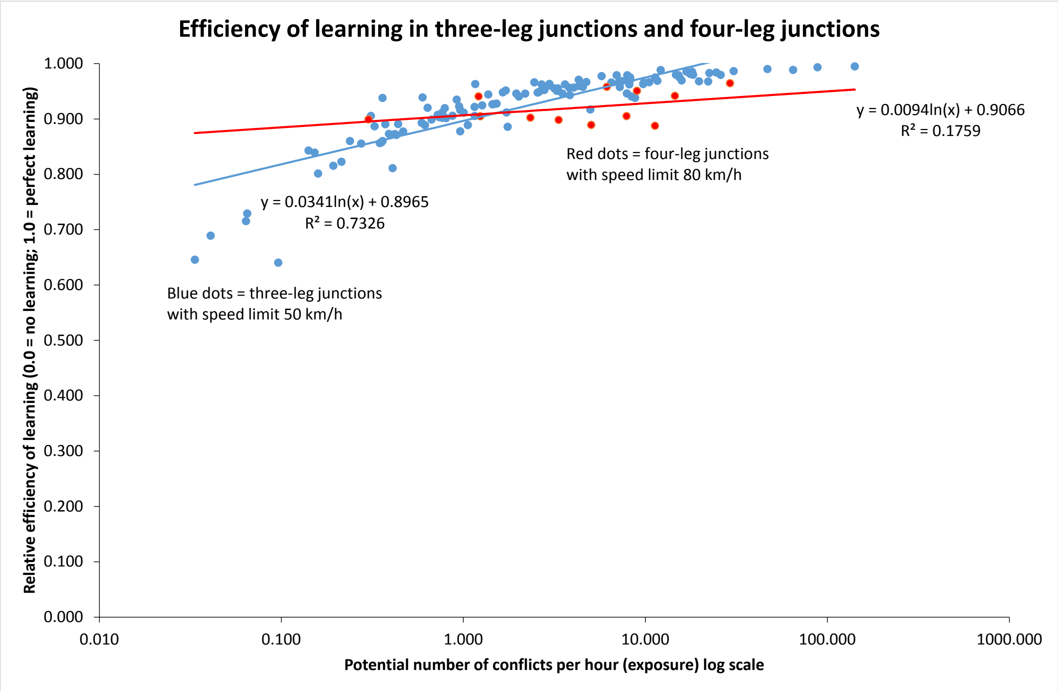

Figure 12: Efficiency of learning in simple and complex junctions

4 Discussion

In a historical perspective, exposure and risk were independent. Exposure was defined as trials, or specific events associated with the potential for accidents. Risk was the probability of an accident at each trial. Thus, in Bortkiewicz' classic study of deaths from horse kicks in the Prussian army, the event was staying sufficiently near a horse to get kicked by it. These events were obviously not all identical in all respects. Sometimes soldiers stayed close to the horse for a long time, which one would expect to entail a greater probability of being kicked than staying close to the horse for only a short while. Sometimes the horse might get scared by an event beyond the control of a soldier; this might also make kicks more likely. Sometimes a soldier would be bent over, making it more likely that a kick would strike the soldier's head than if the soldier was upright. Sometimes the distance would be short enough to be hit by a kick, but perhaps with a less than lethal force. Despite all these, and perhaps many other differences between the events, they were in principle countable. It thus made sense to apply the concept of probability defined as the long-term proportion of events in which the outcome was a fatal kick.

It is highly likely that Bortkiewicz knew neither the number of events nor the probability that each event would lead to a fatal kick. He could, however, make the assumption that the number of events – soldiers staying close to horses – was high and that the probability of a fatal kick was low. Moreover, it appeared reasonable to assume that the probability of a fatal kick was independent of the number of events, i.e. learning in the ordinary sense of the term did not take place. The combination of these assumptions implied that the number of deaths from horse kicks would follow the Poisson distribution. This was indeed what Bortkiewicz found: the empirical distribution of the number of deaths from horse kicks per company per year was very close to the Poisson distribution.

It has long been understood that exposure and risk are not independent in road traffic. When summary measures of exposure, such as vehicle kilometres of travel, are used, it does not make sense to interpret accident rates as estimators of probability. In fact, the long-standing use of summary measures of exposure combined with accident rates severs entirely the conceptual and logical connection between the elementary concepts of probability theory and the empirical estimators of these concepts as developed in road safety studies. It is obviously convenient – in view of data availability – to use vehicle kilometres, or the number of vehicles entering a junction, as a measure of exposure and accident rates as a measure of the probability of accidents. However, neither of these measures have any theoretical foundation in probability theory.

There has also for a long time been a search for estimators of exposure that are independent of risk. The advantage of such estimators of exposure is that they restore the appropriateness of estimating the expected number of accidents as the product of exposure and risk. It is only when exposure and risk actually are independent that the product of exposure and risk gives an unbiased estimate of the expected number of accidents.

The main argument made in this report is that the search for an estimator of exposure which is independent of risk is entirely misguided and should be given up. It is an illusion to think that any conceptually and operationally meaningful definition of exposure to the risk of a road accident could be unrelated to risk. The reason for this is very simple. Exposure involves human beings and human behaviour. Human beings learn. It is therefore very unlikely that those who travel a lot will have the same rate of accidents per unit of travel than those who travel only a little.

This point of view applies irrespective of whether the study units are humans or other elements of the traffic system. It may seem strange to use a term like "learning" if we study accidents in junctions. Surely, junctions do not learn anything, do they? No, but most junctions are used by regular travellers. Most traffic is local, and most junctions are likely to be used by more or less the same road users every day. These regular users of a junction may obviously learn something from their repeated exposure to the junction.

This report proposes new definitions of exposure and risk that are intended to re-establish the connection of these concepts to probability theory. This objective requires a definition of exposure as countable events – trials in the terminology of probability theory – and a definition of risk that can be interpreted as a probability and will be restricted to the interval between 0 and 1.

Traffic is the continuous movement of people and vehicles. It may therefore seem logical and natural to define exposure as a continuous variable. Vehicle kilometres is normally interpreted as a continuous variable, as opposed to a (discrete) count variable. The advantage of using vehicle kilometres as an estimator of exposure is that data are easily available and that the total number of vehicle kilometres produced in a traffic system can be interpreted as an indicator of the total volume of activity in that system. Vehicle kilometres is thus an activity-based estimator of exposure.

Accidents, on the other hand, are a paradigmatic example of a count variable. In textbooks (see, for example, Washington, Karlaftis and Mannering 2011), the count of accidents is very often used as an example of a count variable when, for example, count regression models (Poisson, negative binomial, etc.) are introduced. The relationship between accidents and exposure has traditionally been established by estimating accident rates (accidents per vehicle kilometre), but since this involves dividing a count variable by a continuous variable, the resulting rate cannot be interpreted as a probability. It may, as shown in the introduction, not even be positively related to probabilities. Thus, a high accident rate may be compatible with a low probability of having an accident, and vice versa. Since accident rates have been found to be non-linear, it is not correct that by using accident rates one controls for the effects of traffic volume on the number of accidents. Multiplying an accident rate by varying numbers of vehicle kilometres will, in general, not produce correct estimates of the expected number of accidents.

While it makes perfect sense to view traffic as essentially continuous, in the sense that any partitioning of it into elementary units may be regarded as arbitrary, it is not meaningless to define specific traffic situations as countable events of a quite precise duration and spatial extension. The advantages of defining exposure as specific events are:

1. Most traffic events have a well-defined beginning and end and are therefore countable. The fact that events are countable implies that their total number constitutes a sampling frame (population) from which accidents are sampled

with a certain probability (i.e. some of the events end in accident, some do not).

2. Traffic events represent a potential for an accident to occur. Without the events, there is no such potential. Events are thus estimators of the opportunities for accidents to occur. The total number of events is the total number of opportunities.
3. There are many types of traffic events and some events can usefully be linked to specific types of accidents. Vehicle kilometres of travel, on the other hand, is simply an index of the amount of activity in the system, and can only be linked to the total number of accidents, not to specific types of accident.
4. By providing a concise typology of events, it is possible to obtain a much more detailed description of exposure to risk than summary estimators of exposure afford.
5. Since events are opportunities for accidents to occur, any elementary event has two outcomes: accident, or no accident. This means that the probability of an accident can be defined simply as the proportion of events that have an accident as the outcome. The probability of accident occurrence, thus defined, will always be constrained to the interval 0 to 1.

There are also disadvantages in using events as elementary units of exposure. In the first place, it may not be possible to establish clear links between all types of accidents and specific events. For accidents that cannot be linked to a certain type of event, events cannot be used as an estimator of exposure. In the second place, the definition of some events may be somewhat arbitrary, such as the event of negotiating a curve. One has to specify where the curve begins and ends and how sharp it must be to count as a curve (a curve with a very large radius may not be perceived as a curve, since, once the correct trajectory has been found on the steering wheel, no further steering input is required; in terms of vehicle handling it is therefore identical to driving straight ahead). In the third place, some events may be a compound of two or more elementary events. The issue is then whether the event is of type A or type B or some compound type AB.

Despite these difficulties, it is fruitful to define exposure to the risk of an accident in the following terms:

Exposure is the occurrence of any event in traffic, limited in space and time, that represents a potential for an accident to occur by placing demands on road user cognition.

Cognitive demands span a broad range, but all the events that have been discussed in this report make cognitive demands, even if they do not necessarily require a road user to change behaviour or make a decision. Thus, the cognitive demands represented by oncoming vehicles is to stay in your own driving lane (which at a minimum requires that you look ahead and monitor your lane position; this is automated behaviour in experienced drivers and is not experienced as requiring any effort to be made), but also to check that none of the oncoming vehicles is swerving into your driving lane.

In other situations, like turning into a busy main road, the cognitive demands are very high indeed, requiring the instant processing of data on several traffic movements, judging whether gaps are sufficient, and, at least ideally speaking, double-checking that nothing has been overlooked. In this situation, active observation and decision-making is needed.

It is, if not obvious, then at least highly likely that the relationship between exposure, as defined above, and risk, defined as the probability that an event ends in an accident, will normally be non-linear. In fact, it will be normally be negative. The larger the number of events, the lower the probability of accident occurrence (i.e. the proportion of events that has an accident as the outcome will become lower as the number of events increases). In this report, this tendency has been referred to as a process of learning. Exposure as a process of learning can be defined as follows:

The repeated experience of specific traffic events makes road users familiar with the events; this, in turn, makes road user behaviour in the situations more reliable.

The term reliable means, roughly speaking, error-free. The more reliable human performance becomes, the fewer errors will be made and the lower becomes the proportion of events resulting in an accident. It is taken as axiomatic that no road users wants to become involved in an accident.

The main research tasks in developing a general theory of the relationship between exposure and risk are: (1) to propose specific, empirically testable hypotheses regarding the shape of the relationship between exposure and risk; (2) to model how the interaction between learning and behavioural adaptation shapes the relationship between exposure and risk. This report has started research on these tasks, but represents only the beginning of a large research effort.

There are those who do not accept that the relationship between exposure and risk is non-linear. Thus, af Wåhlberg (2011) argues that non-linearity is a statistical artefact. The analysis he presents to demonstrate this is, however, not very convincing. In a recent paper Paefgen, Staake and Fleisch (2014) argue that vehicle kilometres is a multivariate measure, since some vehicle kilometres are driven in the dark, when risk is higher than in daylight; some kilometres are driven in urban traffic, which has a higher accident rate than rural traffic; some kilometres are driven at high speed, others at low speed, and so on. These points are correct and are, indeed, an argument for not using vehicle kilometres as an estimator of exposure and replacing it by specific events, which, although obviously not identical in minute detail, will at least be much more homogeneous than vehicle kilometres.

Paefgen et al. (2014) present an analysis based on data collected by In-Vehicle Data Recorders. The analysis does not reproduce the monotonous negative relationship between annual driving distance and accident rate per kilometre of driving that many other studies have found. However, the study is a case-control study, in which model coefficients cannot be interpreted as estimators of risk per kilometre driven. Moreover, there is no control for either driver or vehicle characteristics. This is a serious weakness of the study, since it is very likely that there are important differences in driver characteristics between drivers who drive short annual distances and drivers who drive long annual distances.

There is stronger support for the hypothesis that there is a negative relationship between exposure and risk than for any alternative hypotheses regarding the shape of this relationship.

5 Conclusions

The main conclusions of the study presented in this report can be summarised as follows:

1. Conventional measures of exposure and risk (vehicle kilometres and accident rate per vehicle kilometre) have lost their connection with the foundations of accident research in probability theory. Elementary concepts of accident research should be based on probability theory.
2. It is suggested to re-establish the connection between elementary concepts of accident research and probability theory by re-defining the elementary concepts.
3. It is proposed to define exposure as the occurrence of any event, limited in time and space, that has the potential of generating an accident by making demands on road user cognition.
4. Such events include: encounters (vehicles passing each other in opposite directions); simultaneous arrivals at points where road users enter from potential conflicting directions; turning movements in junctions; braking; lane changing; overtaking; negotiating curves.
5. Each of these elementary types of events can be counted and the total number of events can, in terms of probability theory, be regarded as a sampling frame (population) from which accidents are sampled. Each traffic event has two possible outcomes: accident or no accident.
6. The probability of accident occurrence is simply the number of accidents divided by the number of events having an accident as one of its potential outcomes.
7. The probability of an accident is likely to be negatively related to the number of events. The reason for this is that repeated experience of events can be regarded as a process of learning, in which road user performance becomes more and more reliable.
8. Examples are given of empirical studies showing a negative relationship between exposure and risk. These studies lend support to the basic hypotheses proposed in the report, but do not represent stringent tests of these hypotheses in terms of the new definitions proposed for exposure and risk.

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