Rune Elvik

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Institute of Transport Economics
Norwegian Centre for Transport Research

The Power Model of the relationship between speed and road safety

Update and new analyses

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Summary:

The report contains an update and new analyses of the Power Model of the relationship between (changes in) speed and (changes in) road safety. The updated analysis is based on 115 studies containing a total of 526 estimates. The Power Model provides a good description of the relationship between speed and road safety. One version of the model has been developed for roads in urban areas, another version for rural roads and freeways. The effects of changes in speed on road safety are smaller in urban areas than in rural areas. The report analyses the normative foundations of speed limits. It is concluded that speed limits are needed, as a free choice of speed is unlikely to produce outcomes that are optimal from a societal perspective.

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Sammendrag:

Rapporten presenterer en oppdatert analyse av potensmodellen, som beskriver sammenhengen mellom (endringer i) fart og (endringer i) trafikksikkerhet. Den oppdaterte analysen bygger på 115 undersøkelser med til sammen 526 resultater. Potensmodellen gir en god beskrivelse av sammenhengen mellom fart og trafikksikkerhet. Det er skilt mellom en versjon av modellen for veger i byer og tettsteder og en versjon for veger i spredtbygde strøk, samt motorveger. Virkningene av fart på trafikksikkerheten er svakere i byer og tettsteder enn utenfor. Rapporten drøfter også det normative grunnlaget for fartsgrenser. Det konkluderes med at fartsgrenser er nødvendige fordi trafikantenes frie valg av fart ikke vil gi samfunnsmessig ønskede resultater.

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Preface

In 2004, the Institute of Transport Economics published the report: ”Speed and road accidents: an evaluation of the Power Model”, by Rune Elvik, Peter Christensen and Astrid Amundsen (Report 740/2004).

In November 2007, the first author of the report, Rune Elvik, defended it as a dissertation for the degree philosophiae doctor (Ph. D.) at Aalborg University in Denmark. On that occasion, he announced an intention to update the study. This report contains an updated analysis of the relationship between speed and road safety and an updated evaluation of the Power Model.

Although several models may adequately describe the relationship between speed and road safety, the Power Model is retained in this report because of its parsimony and simplicity. The model is, however, refined by proposing one version that applies to urban or residential roads and one version that applies to rural roads and freeways. The exponents that constitute the core of the model have been revised. In general, the effects of speed on road safety appear to have become slightly weaker in recent years. Despite this, speed remains a very important risk factor for accidents and injuries. In many motorised countries, speeding is one of the biggest road safety problems.

The report also provides a re-statement of the case for speed limits. It is argued that although drivers may be subjectively rational when choosing speed, their choices are likely to be based on preferences that are influenced by many factors that must be regarded as irrelevant when determining the speeds that are optimal from a societal point of view, as well as an erroneous perception of important impacts of speed. The discussion resurrects a distinction between subjective and objective rationality which is rarely made in analyses relying on the assumption that individual choices are rational.

The study was funded by the Research Council of Norway. Rune Elvik was project manager and is the author of this report. Statistician Peter Christensen contributed by performing meta-regression analyses. Head of Department Marika Kolbenstvedt was responsible for quality assessment of the report. Secretary Trude Rømming performed final editing of the report and prepared it for printing.

Oslo, September 2009
Institute of Transport Economics

Lasse Fridstrøm
Managing Director

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Head of Department

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Summary:

The Power Model of the relationship between speed and road safety

Update and new analyses

The Power Model remains a valid model of the relationship between speed and road safety according to new analyses presented in this report. The effects on road safety of changes in speed are found to vary depending on initial speed. In general, changes in speed have a smaller effect at low speeds than at high speeds.

Background and research problem

In 2004, the Institute of Transport Economics published the report: "Speed and road accidents: an evaluation of the Power Model" (report 740/2004). In 2007, the first author of that report, Rune Elvik, defended it for the degree Ph. D. at Aalborg University. He then announced his intention to update the study.

This report presents an updated analysis of the relationship between speed and road safety. The original analysis was based on 98 studies containing a total of 460 estimates of the effect on road safety of changes in speed. This report is based on 115 studies containing 526 estimates of effect. The following questions are the focus of the study:

1. Does the Power Model adequately describe the relationship between changes in speed and changes in road safety, or should it be replaced by a different model?
2. Is a revision of the Power Model, in particular the values of the exponents that form the core of the model, justified?

In addition to analysing these questions, the report discusses a number of other issues, including the normative basis of speed limits (as opposed to not regulating the choice of speed).

The Power Model

The Power Model was proposed by the Swedish researcher Göran Nilsson. The model describes the relationship between changes in speed and changes in the number of accidents or the number of accident victims in terms of six power functions, all of which have the following form:

$$\frac{Accidents\ after}{Accidents\ before} = \left(\frac{Speed\ after}{Speed\ before}\right)^{Exponent}$$

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The relative change in the number of accidents (or killed or injured road users) is estimated by raising the relative change in speed to an exponent. The value of the exponent varies according to accident- or injury severity.

The Power Model is a monotonic function, i.e. the value of the function increases throughout the range. Or to say it more colloquially: The higher the speed, the greater the number of accidents. And conversely: The lower the speed, the lower the number of accidents. Speed refers to the mean speed of traffic.

Re-analysis, update and development

Three re-analyses of the original study have been made. One by Ezra Hauer, one by James Bonneson, and one by Max Cameron and Rune Elvik. All these re-analyses conclude that the effect of a given relative change in speed (e.g. −10 %) depends on the initial level of speed. This is not consistent with the Power Model. A tendency is seen for changes in relatively low speeds (below about 60 km/h) to have smaller effects on safety than changes in relatively high speeds (above about 60 km/h). This suggests that one should either abandon the Power Model in favour of a model which is consistent with varying effects of given relative changes in speed – like the logistic model – or develop several versions of the Power Model adopted to varying levels of initial speed. One type of model that can accommodate varying effects of speed is a Box-Cox model, in which the curvature of the relationships between two variables is permitted to vary continuously.

Although the updated study was not based on a dramatically larger number of studies (115 versus 98) or estimates of effect (526 versus 460) than the original study, the findings do differ from the original study with respect to at least two key factors.

In the first place, the exponents are found to vary depending on initial speed. In order to capture this, two new versions of the Power Model have been developed. One version applies to urban and residential roads, the other version applies to rural roads and freeways. In addition, a version applying to all roads has been kept. In the second place, the values of the exponents have been adjusted. There is tendency for the exponents to become smaller over time, suggesting that the effects of speed are also becoming smaller. It is nevertheless clear that speed remains a very important risk factor both for accident occurrence and injury severity.

The revised Power Model

Table S.1 presents exponents that have been developed for the revised Power Model. Nearly all the exponents are very close to study estimates. The exponents referring to all injury accidents and to all injured road users have been adjusted downwards, in order to be consistent with the exponents referring to specific levels of accident- or injury severity. The exponents are somewhat lower than those found in the original study.

Table S1: Exponents for the revised Power Model

	Summary estimates of exponents by traffic environment					
	Rural roads/freeways		**Urban/residential roads**		**All roads**	
Accident or injury severity	**Best estimate**	**95 % confidence interval**	**Best estimate**	**95 % confidence interval**	**Best estimate**	**95 % confidence interval**
Fatal accidents	4.1	(2.9, 5.3)	2.6	(0.3, 4.9)	3.5	(2.4, 4.6)
Fatalities	4.6	(4.0, 5.2)	3.0	(-0.5, 6.5)	4.3	(3.7, 4.9)
Serious injury accidents	2.6	(-2.7, 7.9)	1.5	(0.9, 2.1)	2.0	(1.4, 2.6)
Seriously injured road users	3.5	(0.5, 5.5)	2.0	(0.8, 3.2)	3.0	(2.0, 4.0)
Slight injury accidents	1.1	(0.0, 2.2)	1.0	(0.6, 1.4)	1.0	(0.7, 1.3)
Slightly injured road users	1.4	(0.5, 2.3)	1.1	(0.9, 1.3)	1.3	(1.1, 1.5)
Injury accidents – all	1.6	(0.9, 2.3)	1.2	(0.7, 1.7)	1.5	(1.2, 1.8)
Injured road users – all	2.2	(1.8, 2.6)	1.4	(0.4, 2.4) #	2.0	(1.6, 2.4)
PDO- accidents	1.5	(0.1, 2.9)	0.8	(0.1, 1.5)	1.0	(0.5, 1.5)

Confidence interval specified informally
Source: TØI-report 1034/2009

The normative foundations of speed limits

The report contains an analysis of the normative foundations of speed limits. The starting point of the analysis is the assumption that road users are rational in choosing speed. A distinction is made between subjective and objective rationality. This distinction is very rarely made in modern analyses relying on the theory of rational choice, but it makes perfect sense with respect to the choice of speed. It is argued that if road users are objectively rational in the choice of speed, the outcome will be optimal from a societal point of view and no speed limits are needed. Analysis shows, however, that road user choice of speed does not satisfy the requirements of objective rationality (although it is possible to model the choices as being subjectively rational). On this basis, it is concluded that speed limits are needed in order to guide road users in their choices so as to obtain more optimal outcomes.

It should be noted that the term “optimal outcomes” is equivalent to optimal speed from a socio-economic point of view. The choice of speed can be approached from many perspectives, and the choice of a perspective based on economic welfare theory in this report is clearly not meant to suggest that other perspectives cannot provide useful insights.

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Sammendrag:

Potensmodellen for sammenhengen mellom fart og trafikksikkerhet

En oppdatering

Potensmodellen er fortsatt en gyldig modell for å beskrive sammenhengen mellom fart og trafikksikkerhet. Det viser nye analyser som legges fram i denne rapporten. Virkningene på trafikksikkerheten av endringer i fart varierer med hvor høy farten er i utgangspunktet. Endringer fra en lav fart har mindre virkninger på trafikksikkerheten enn endringer fra en høy fart.

Bakgrunn og problemstilling

I 2004 utga Transportøkonomisk institutt rapporten: ”Speed and road accidents: an evaluation of the Power Model” (rapport 740/2004). I 2007 ble rapporten forsvart som doktoravhandling ved Aalborg Universitet av dens førsteforfatter, Rune Elvik. Han gjorde det da kjent at han tok sikte på å oppdatere undersøkelsen.

Denne rapporten inneholder en oppdatert analyse av sammenhengen mellom fart og trafikksikkerhet. I den opprinnelige studien inngikk 98 undersøkelser med til sammen 460 resultater. Den oppdaterte analysen bygger på 115 undersøkelser med til sammen 526 resultater. Hovedproblemstillingene er:

1. Gir Potensmodellen en tilstrekkelig god beskrivelse av sammenhengen mellom endringer i fart og endringer i trafikksikkerhet, eller bør den erstattes av en annen modell?
2. Er det grunnlag for å videreutvikle Potensmodellen og endre tallverdiene av eksponentene som danner hovedinnholdet i modellen?

I tillegg til disse spørsmålene drøfter også rapporten en del andre temaer, herunder det normative grunnlaget for å ha fartsgrenser fremfor å tillate fri fart.

Potensmodellen

Potensmodellen er utviklet av den svenske trafikksikkerhetsforskeren Göran Nilsson. Den beskriver sammenhengen mellom endringer i fart og endringer i antallet ulykker eller antallet skadde eller drepte personer i form av seks potensfunksjoner som alle har følgende form:

$$\frac{Ulykker\ etter}{Ulykker\ før} = \left(\frac{Fart\ etter}{Fart\ før}\right)^{Eksponent}$$

Man finner den relative endringen i antall ulykker (eller tilskadekomne) som følge av en gitt relativ endring i fart ved å opphøye fartsendringen i en eksponent. Tallverdien av eksponenten varierer etter ulykkenes eller skadenes alvorlighetsgrad.

Potensmodellen beskriver en monoton funksjon, det vil si en funksjon som stiger i hele sitt definisjonsområde. Eller sagt litt enklere: jo høyere fart, desto flere ulykker, uansett hvilket nivå farten er på i utgangspunktet. Og omvendt: jo lavere fart, desto færre ulykker.

Re-analyse, oppdatering og videreutvikling

Det er gjort tre re-analyser av den opprinnelige analysen som ble publisert i TØI-rapport 740/2004. Disse tre re-analysene er gjort av (1) Ezra Hauer, (2) James Bonneson og (3) Max Cameron og Rune Elvik. Alle de tre analysene kommer til at virkningen av en gitt relativ endring i fart (for eksempel 10 % reduksjon) ikke er uavhengig av fartsnivået før endringen, slik Potensmodellen forutsetter. Det er en tendens til at endringer fra en relativt lav fart (under ca 60 km/t) har mindre virkninger på ulykkene enn endringer fra en relativt høy fart (over 60 km/t). Dette tilsier at man enten bør oppgi Potensmodellen til fordel for en modell som er forenlig med at virkningen av en gitt relativ endring i fart varierer med fartsnivået – eksempelvis en logistisk funksjon – eller at det bør utvikles ulike varianter av Potensmodellen for ulike fartsnivåer.

Den opprinnelige undersøkelsen, samt re-analysene av denne, var basert på 98 undersøkelser med til sammen 460 resultater. Oppdateringen bygger på 115 undersøkelser med til sammen 526 resultater. Selv om antallet nye undersøkelser og resultater er begrenset, viser det seg at resultatene av den oppdaterte analysen skiller seg fra resultatene av den opprinnelige analysen på en del viktige punkter.

For det første viser det seg at verdiene av eksponentene varierer betydelig avhengig av fartsnivået i utgangspunktet. For å fange opp dette, er et nytt sett av eksponenter beregnet for veger i tettbygde strøk og boligområder, landeveger og motorveger, samt alle veger. For det andre viser det seg at tallverdiene av eksponentene bør justeres. Jevnt over er eksponentene noe lavere enn i den opprinnelige analysen, noe som tyder på at virkningene av endringer i fart er litt redusert over tid. Det er likevel klart at endringer i fart har store virkninger for trafikksikkerheten.

En revidert Potensmodell

Tabell S.1 viser eksponenter som foreslås benyttet, samt 95 % konfidensintervaller for disse, i den reviderte potensmodellen. De oppgitte eksponentene ligger i de fleste tilfeller nær resultatene av undersøkelsen. Eksponentene for alle personskadeulykker og alle skadde personer er imidlertid rundet av nedover for å være innbyrdes konsistente med eksponentene som gjelder for dødsulykker, ulykker med alvorlig skadde personer og ulykker med lettere skadde personer. Jevnt over er eksponentene noe lavere enn i den opprinnelige studien.

Tabell S.1: Eksponenter i revidert Potensmodell

	Eksponenter etter trafikkmiljø					
	Landeveger/motorveger		**Veger i tettbygd strøk**		**Alle veger**	
Ulykkers eller skaders alvorlighetsgrad	**Beste anslag**	**95 % konfidens-intervall**	**Beste anslag**	**95 % konfidens-intervall**	**Beste anslag**	**95 % konfidens-intervall**
Dødsulykker	4.1	(2.9, 5.3)	2.6	(0.3, 4.9)	3.5	(2.4, 4.6)
Drepte	4.6	(4.0, 5.2)	3.0	(-0.5, 6.5)	4.3	(3.7, 4.9)
Ulykker med alvorlig personskade	2.6	(-2.7, 7.9)	1.5	(0.9, 2.1)	2.0	(1.4, 2.6)
Alvorlig skadde personer	3.5	(0.5, 5.5)	2.0	(0.8, 3.2)	3.0	(2.0, 4.0)
Ulykker med lett personskade	1.1	(0.0, 2.2)	1.0	(0.6, 1.4)	1.0	(0.7, 1.3)
Lettere skadde personer	1.4	(0.5, 2.3)	1.1	(0.9, 1.3)	1.3	(1.1, 1.5)
Alle personskadeulykker	1.6	(0.9, 2.3)	1.2	(0.7, 1.7)	1.5	(1.2, 1.8)
Alle skadde personer	2.2	(1.8, 2.6)	1.4	(0.4, 2.4) #	2.0	(1.6, 2.4)
Ulykker med kun materiell skade	1.5	(0.1, 2.9)	0.8	(0.1, 1.5)	1.0	(0.5, 1.5)

Konfidensintervall anslått uformelt

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Det normative grunnlaget for fartsgrenser

Fartsgrenser finnes i dag nesten overalt: kun deler av motorvegene i Tyskland har fri fart. Det kan derfor synes som en anakronisme å reise spørsmålet om fartsgrenser trengs, eller om man kan la trafikantene fritt velge sin fart. Hvis man tar utgangspunkt i en antakelse om at trafikantene er rasjonelle i valg av fart, er fartsgrenser overflødige hvis trafikantenes valg gir samfunnsmessig ønskede resultater. Betingelsen for dette er at trafikantene er objektivt rasjonelle i valg av fart, ikke bare subjektivt rasjonelle. I moderne analyser som bygger på en antakelse om rasjonell handling skilles det nesten aldri mellom subjektiv og objektiv rasjonalitet. Et slikt skille gir imidlertid mening når det gjelder analyser av fartsvalg. I rapporten påvises klare og systematiske forskjeller mellom subjektivt og objektivt rasjonelt valg av fart, noe som tilsier at trafikantenes subjektivt rasjonelle valg ikke vil gi samfunnsmessig ønskede resultater. Dette tilsier at trafikantenes fartsvalg bør begrenses i form av fartsgrenser.

Det understrekes at begrepet ”ønskede resultater” i denne forbindelse kan tolkes som optimalt fartsvalg fra et samfunnsøkonomisk perspektiv. Trafikanters valg av fart kan studeres ut fra mange perspektiver som alle gir innsikt. Valget av en samfunnsøkonomisk referanseramme for analysen er selvsagt ikke uttrykk for en oppfatning om at andre perspektiver har mindre verdi.

1 Background and research problem

1.1 The 2004-evaluation of the Power Model

In late 2004, the report “Speed and road accidents: an evaluation of the Power Model” (Elvik, Christensen and Amundsen 2004) was published. The report contained an evaluation of the Power Model of the relationship between changes in speed and changes in road safety, proposed by Göran Nilsson (2004). The Power Model describes the relationship between changes in the mean speed of traffic and changes in the number of accidents or accident victims in terms of a set of power functions.

The evaluation of the Power Model relied on a meta-analysis of 98 studies containing a total of 460 estimates of the relationship between changes in speed and changes in road safety. Broadly speaking, the Power Model was supported, but the values of some of the exponents were slightly different from those proposed by Nilsson.

In 2007, the report containing the evaluation of the Power Model was submitted as a dissertation for the degree of philosophiae doctor (PhD) at Aalborg University in Denmark. The report was assessed as appropriate for a PhD dissertation, and a public defence was held on November 2, 2007. The senior author of the report, Rune Elvik, thus earned the PhD degree.

On the occasion of the public defence for the PhD degree, Elvik announced his intention to update the study. This report presents an update of the Power Model.

1.2 Main research problems addressed in this report

The main research problems addressed in this report are:

1. Do the main findings of the 2004-study withstand critical scrutiny? What are the findings of re-analyses of the 2004-study?
2. What are the findings of new studies that have been published after the 2004-study? Does an analysis of new studies produce results that differ from those reported in 2004?
3. How does synthesising new studies and the studies included in 2004 modify the main results? Are the estimates of power stable over time?
4. Do other models describe the relationship between speed and road safety more precisely than the Power Model? Is individual driver speed related to accident occurrence the same way as the mean speed of traffic? Does speed variance contribute to accident occurrence?
5. Can the case for speed limits be argued in terms of lack of driver rationality with respect to choice of speed? Is driver speed choice rational?

Which are the factors that influence driver speed choice? Do all driver have the same preferences with respect to the choice of speed?

2 A chapter has been devoted to each of the main research problems.

2 Re-analyses of the 2004-data

There have been three re-analyses of the data used in the evaluation of the Power Model in 2004. Two of these was reported by Hauer and Bonneson (2006), the third by Cameron and Elvik (2008).

2.1 The re-analyses by Hauer and Bonneson

Hauer and Bonneson (2006) reported re-analyses of the data that served as the basis for the 2004-evaluation of the Power Model. They conducted the analyses separately, but both analyses were presented in the same report.

Hauer concluded that the effect on accidents of changes in speed depend on the initial level of speed and on the type of traffic environment. He developed an exponential model to account for these variations. The main findings of his analysis are reproduced in Table 1, which compares his estimates of the effects of changes in speed to those reported by Elvik, Christensen and Amundsen (2004). A ten percent reduction in speed is used as an example in the Table.

The Power Model predicts a constant effect of a ten percent reduction in speed; the effect is independent both of initial speed and type of traffic environment. According to the Power Model, the effects of a given percentage change in speed vary only according to accident or injury severity. The effect is slightly larger for accident victims than for accidents.

Hauer proposed the following model for the effect of changes in speed:

$$\text{Ln(AMF)} = (b_1 I_i + b_2 I_f)\ln(v_{after}/v_{before}) - b_3(1/v_{after} - 1/v_{before}) \qquad (1)$$

AMF is an accident modification factor. A value of, for example, 0.8 corresponds to an accident reduction of 20%. Ln is the natural logarithm, b_1 and b_2 are coefficients for indicator variables for injury accident (I_i) or fatal accidents (I_f), b_3 is a coefficient representing critical manoeuvre speed, which is the speed at which a critical manoeuvre to avoid an accident is assumed to take place. This is equal to 70.9 miles per hour for freeways and rural highways and to 19.7 miles per hour for urban arterial roads.

Residential streets were not included in the re-analysis. Furthermore, freeways and rural highways were merged to one group. 323 of the original 460 estimates of the relationship between speed and road safety were included in the re-analysis.

Table 1: Comparison of best estimates of expected changes in the number of accidents as estimated by Hauer (2006) and by Elvik, Christensen and Amundsen (2004).

		Original 2004-analysis		**2006-re-analysis**	
Initial speed (mph)	**New speed (mph)**	**Urban arterials**	**Freeway or rural highway**	**Urban arterials**	**Freeway or rural highway**
		Estimates for fatal accidents			
30	27	−32%	−32%	−30%	−42%
40	36	−32%	−32%	−29%	−38%
50	45	−32%	−32%	−28%	−36%
60	54	−32%	−32%	−28%	−34%
70	63	−32%	−32%	−27%	−33%
		Estimates for injury accidents			
30	27	−19%	−19%	−19%	−33%
40	36	−19%	−19%	−18%	−29%
50	45	−19%	−19%	−17%	−26%
60	54	−19%	−19%	−16%	−24%
70	63	−19%	−19%	−16%	−23%
		Estimates for property-damage-only accidents			
30	27	−10%	−10%	−16%	−31%
40	36	−10%	−10%	−15%	−26%
50	45	−10%	−10%	−14%	−23%
60	54	−10%	−10%	−13%	−21%
70	63	−10%	−10%	−13%	−20%

As can be seen from Table 1, the re-analysis produced results that differ from the original analysis. The main differences are:

1. The effects of changes in speed were found to vary according to initial speed, accident severity and type of traffic environment.
2. The effects of a given percentage change in speed is larger at low speeds than at high speeds.
3. The effects of changes in speed are larger than predicted by the Power Model for freeways and rural highways.
4. The effects of changes in speed tend to be slightly smaller than predicted by the Power Model for fatal accidents and injury accidents on urban arterial roads.
5. The effects of changes in speed are larger for property damage only accidents than predicted by the Power Model.

The revised model fit the data marginally better than the Power Model ($R^2 = 0.55$ versus $R^2 = 0.54$).

A second re-analysis was reported by James Bonneson. Bonneson derived a function predicting the accident modification factor attributable to a change in speed by solving a set of differential equations. The following function was derived:

$$\mathrm{AMF} = e^{\alpha\left[v - v^* + \frac{\beta}{2}(v^2 - v^{*2})\right]} \qquad (2)$$

The function is exponential (e raised to the power of the expression in brackets), α and β are parameters to be estimated, v is initial speed and v* is speed after a change. For fatal accidents, α was estimated to 0.2666 and β to −0.0098.

The predicted changes in the number of fatal accidents for the speed changes used as examples in Table 1 are:

- Changing speed from 70 to 63 miles per hour reduces fatal accidents by 48 percent.
- Changing speed from 60 to 54 miles per hour reduces fatal accidents by 51 percent.
- Changing speed from 50 to 45 miles per hour reduces fatal accidents by 51 percent.
- Changing speed from 40 to 36 miles per hour reduces fatal accidents by 49 percent.
- Changing speed from 30 to 27 miles per hour reduces fatal accidents by 44 percent.

Applying equation 2 to changes from 20 to 18 miles per hour and from 80 to 72 miles per hour (both of which are 10 percent reductions) shows that the effect on fatal accidents is estimated to be a 35 % reduction for a speed reduction from 20 to 18 miles per hour, and a 42 % reduction for a speed reduction from 80 to 72 miles per hour. In other words, smaller effects are predicted for given percentage changes in low and high speeds than for identical percentage changes in intermediate speeds. This is consistent with a logistic model of the relationship between speed and road safety. In general, the effects for fatal accidents predicted by Bonneson's model are considerable larger than those predicted by the Power Model. Bonneson did not make any distinction between different types of traffic environment.

For injury accidents, a model of the same form was developed, but the parameter α was estimated to the value of 0.0838 and the parameter β to the value of −0.0051. The predicted effects of a ten percent reduction in speed on the number of injury accidents decline monotonically as initial speed declines. For initial speeds between 70 miles per hour and 30 miles per hour, the predicted reductions of injury accidents range from 32 % (70 miles) to 19 % (30 miles). All these estimates predict greater effects than the Power Model. No distinction was made between different types of traffic environment.

For property damage only accidents, Bonneson was not able to develop a model.

2.2 The re-analysis by Cameron and Elvik

Max Cameron and Rune Elvik re-analysed the original data by stratifying weighted mean estimates of the exponent in the Power Model according to type of traffic environment. The results of his re-analysis appear in Table 2.

Table 2: Re-analysis of the Power Model by Cameron. Best estimates of power by type of traffic environment

	Traffic environment of study				
Power estimates (standard error SE)	**Urban**	**Rural**	**Resi-dential**	**Freeway**	**All studies**
Mutually exclusive categories					
Fatalities	4.251	4.711	NA	4.931	4.902
SE	*0.92*	*0.49*		*0.15*	*0.14*
Seriously injured	1.390	1.805	*3.767*	*3.859*	1.593
SE	*0.24*	*0.30*			*0.18*
Slightly injured	1.928	1.554	*1.522*	*3.604*	1.742
SE	*0.25*	*0.24*			*0.17*
Injured (unspecified)	*6.108*	5.480	NA	2.770	2.780
SE		*0.44*		*0.03*	*0.03*
Cumulative categories					
Fatalities	4.251	4.711	NA	4.931	4.902
SE	*0.92*	*0.49*		*0.15*	*0.14*
Fatal and serious injury (cumulated)	1.569	2.592		4.925	3.721
SE	*0.23*	*0.26*		*0.14*	*0.11*
All levels of injury severity (cumulated)	1.746	2.495		2.839	2.806
SE	*0.17*	*0.16*		*0.03*	*0.03*
Specific injured (non-fatal)			2.829		
SE			*1.45*		

Source: TØI-report 1034/2009

Power estimates in italics were each based only on one study of effect of speed change

Among the reliable estimates, it can be seen that substantially higher powers were estimated for freeways and rural highways than urban roads. The high-speed freeway environment is associated with particularly high power estimates across all levels of injury. Rural highways are reasonably consistent with Nilsson's power model, with the cumulative estimates (i.e. estimates in which fatal and serious injuries are combined, and fatal, serious and slight injuries are combined) decreasing monotonically from 4.71 for fatalities to 2.59 for serious casualties and 2.50 for all casualties. The power estimates for the mutually exclusive injury categories are also consistent with the monotonic decrease found by Elvik et al. (2004), ignoring the relatively high, but potentially unreliable estimate for injured (unspecified) road users.

It is on urban roads that the expected monotonic relationship of the power estimates breaks down. The power estimate for the seriously injured victims was only 1.39, compared with 1.93 for the slightly injured. The power estimate for fatalities was also substantially less than that on rural highways and freeways, but it was associated with a relatively high standard error. Based on 95% confidence limits of about twice the standard error in each case, none of the power estimates for the mutually-exclusive injury categories on urban roads was statistically different from the corresponding estimate across all studies and road environments.

The power estimates based on the cumulative injury categories have the advantage that each of the non-fatal estimates is contributed to by a substantial number of studies and improves the precision of estimation lost due to sub-dividing the studies by the road environment. In this analysis there is stronger evidence of smaller power estimates associated with the studies on urban roads. The power estimate of 1.57 for serious casualties on urban roads is statistically significantly less than that on rural highways (2.59), and that is statistically significantly less than the power estimate on freeways (4.93), as indicated by non-overlapping confidence limits for each comparison. There is evidence of similar differences in the power estimates for the all casualties category across these three road environments.

As a further test on the validity of these estimates of power, Elvik contributed to the re-analysis by presenting a set of estimates based on meta-regression analysis performed in Elvik et al. (2004). These estimates appear in Table 3.

Table 3: Power estimates for accidents and accident victims based on meta-regression analysis

	Type of traffic environment				
Estimates of power	**Urban**	**Rural**	**Residential**	**Freeway**	**All areas**
Fatalities	3.60	5.90	4.84	5.33	4.26
Seriously injured	2.67	4.96	3.90	4.40	3.32
Slightly injured	0.90	3.19	2.13	2.63	1.55
Injured (unspecified)	0.54	2.83	1.77	2.26	1.19
Fatal accidents	2.06	4.36	3.30	3.79	2.72
Serious accidents	0.49	2.78	1.72	2.22	1.14
Slight accidents	-0.07	2.22	1.16	1.66	0.58
Injury accidents	1.25	3.54	2.48	2.98	1.90

Source: TØI-report 1034/2009

The meta-regression model was very comprehensive and included, in addition to estimates of power applying to all categories of accident- or injury severity (treated as mutually exclusive categories), coefficients capturing the effects of road environment, study design, publication type, decade in which study was reported, and use of other measures to influence speed in addition to speed limits. The estimates in Table 3 were derived by combining the constant term, the coefficients for the various levels of accident- or injury severity and the coefficients for type of traffic environment. The coefficients for the other variables included in the model were not used.

Broadly speaking, the results are consistent with the Power Model, but they confirm clearly lower values for the exponent in urban areas.

2.3 Main findings of the re-analyses and issues for further research

The main findings of the re-analyses presented above can be summarised as follows:

1. The effects of a given percentage change in speed depend on initial speed. This was found both by Hauer and by Bonneson. This finding is inconsistent with the Power Model.
2. The effects of a given percentage change in speed vary according to the type of traffic environment. Effects tend to be lower in urban areas than in rural areas and on freeways. This was found by Hauer and Cameron. This finding is not necessarily inconsistent with the Power Model, but it does suggest that a single set of exponents may not apply to all types of traffic environment.
3. The effects of a given percentage change in speed appear to be greater for fatal accidents than predicted by the estimates of power developed in the original analysis.
4. The effects of a given percentage change in speed appear to be greater for injury accidents, at least in rural areas and on freeways, than predicted by the exponents fitted for the Power Model in 2004.
5. In urban areas, the effects of a given percentage change in speed do not appear to be larger for serious injuries than for slight injuries.

These findings suggest that further research should focus on the following questions regarding the relationship between speed and road safety:

1. Does the effect of changes in speed vary depending on initial speed? More particularly: is there evidence that the effects of changes in speed are smaller at very high and very low levels of speed than at intermediate levels of speed?
2. Does the effect of changes in speed vary according to type of traffic environment?
3. Is the effect of changes in speed uniformly larger for serious injuries than for slight injuries, or does this gradient only apply in rural areas and on freeways?

3 New studies of speed and road safety

3.1 Sources of information about new studies

New studies dealing with the relationship between speed and road safety have been identified by scanning the following sources of information:

- The SafetyLit weekly newsletter. This newsletter lists recently published papers in scientific journals dealing with safety-related topics.
- The Transportation Research Board weekly newsletter. This newsletter is particularly useful in covering the “grey” literature in the United States.
- Manuscripts submitted to and published in Accident Analysis and Prevention.

In addition to using these sources of information systematically, reference lists in relevant studies have been examined. No new search of any literature database has been performed. Several new studies have been identified, in addition to a few studies that were missed in the original study.

3.2 New studies included in meta-analysis

Table 4 lists new studies that were retrieved and provided sufficient information be included in a meta-analysis. A total of 17 studies were found, containing a total of 66 estimates of the relationship between speed and road accidents. The number of estimates extracted from each study varies between 1 and 12. One of the studies (Reiff et al 2008) was entered in re-analysed form (Elvik 2008). Six countries are represented among the studies: Australia, Denmark, Great Britain, Norway, Switzerland and the United States. Several studies have evaluated the effects of speed cameras, which have become more widely used in recent years. The studies were coded according to the same codebook as the original study.

The quality of the studies appears to be slightly better than in the original analysis. Four potential sources of bias were considered: (1) Regression-to-the-mean, (2) Long-term trends, (3) Changes in traffic volume, and (4) Confounding by other risk factors. For each study, an assessment was made as to whether the source of bias was likely to be present in the study or not. 26 of the 66 estimates were judged not to be influenced by any of the sources of error, which corresponds to 39.4 %. In the 2004-analysis, 34.1 % of estimates were judged to be free of bias.

Table 4: Studies of the relationship between changes in speed and changes in road safety included in update of the Power Model

Authors	Year	Country	Measure evaluated	Number of estimates of effect
Dart	1977	United States	Speed limit	3
Ewing	1999	United States	Traffic calming (humps)	4
Povey, Frith and Keall	2003	New Zealand	Police enforcement	2
Webster and Layfield	2003	Great Britain	Traffic calming (humps)	6
Mountain, Hirst and Maher	2004	Great Britain	Speed cameras	1
Cunningham, Hummer, Moon	2005	United States	Speed cameras	6
Gains et al.	2005	Great Britain	Speed cameras	1
Lindemann	2005	Switzerland	30 kmh zones	2
Mountain, Hirst and Maher	2005	Great Britain	Speed cameras, etc.	3
Kockelman	2006	United States	Speed limits	3
Long et al.	2006	Australia	Speed limits	6
Bobevski et al.	2007	Australia	Police enforcement	2
Christensen and Ragnøy	2007	Norway	Speed limits	3
D'Elia, Newstead, Cameron	2007	Australia	Police enforcement	2
Kloeden, Woolley, McLean	2007	Australia	Speed limit	12
Reiff et al. (Elvik)	2008	Denmark	Speed limit	8
Shin, Washington, Schalkwyk	2009	United States	Speed cameras	2

Source: TØI-report 1034/2009

3.3 New studies not included in meta-analysis

In addition to the new studies included in the meta-analysis, a number of studies were retrieved that could, for various reasons, not be included in the meta-analysis. Table 5 lists these studies and the reason for not including them in the meta-analysis.

Studies were omitted because they did not include all data needed to include them in meta-analysis. No study was omitted because it was methodologically weak. In total, 13 studies were omitted. This is only slightly less than the number of studies that was included (17). This shows that the reporting of study findings is still not always sufficiently detailed or precise to allow studies to be included in meta-analysis. There is, however, no reason to believe that the omission of the studies listed in Table 5 has introduced any bias in the study.

3.4 Results of meta-analysis

Meta-analysis was performed, based on the 17 studies listed in Table 4. The analysis treated the various levels of accident- or injury severity as mutually exclusive categories, not as cumulative levels, as proposed by Nilsson (2004).

The results turned out to be very heterogeneous and a random effects model was applied to obtain summary estimates of power in all categories. Table 6 lists the main findings.

Table 5: Studies not included in the meta-analysis and reason for exclusion

Author	Year	Country	Reason for exclusion
Fieldwick, Brown	1987	Several	No data on speed; standard errors not stated
Nolf et al.	1998	United States	Accident severity not stated
Hess	2004	Great Britain	No speed data; highly unconventional analysis
Federal Highway Adm.	2004	United States	Number of accidents not stated
Chen	2005	United States	Too imprecise data
Engeln et al.	2005	Germany	No accident data
Pilkington, Kinra	2005	Several	Too imprecise data
Wong et al.	2005	Hong Kong	No speed data
Davis et al.	2006	Two countries	Relates to individual accidents, not traffic speed
Lindkvist	2006	Sweden	No accident data
Friedman et al.	2007	Israel	Too imprecise speed data
Grabowki, Morrisey	2007	United States	No speed data
Malyshkina, Mannering	2008	United States	No speed data; no accident data

Source: TØI-report 1034/2009

Table 6 presents summary estimates of power obtained in four ways:

1. By means of a fixed-effects model of meta-analysis
2. By means of a random-effects model of meta-analysis
3. As a simple mean (not weighted)
4. As the simple median (not weighted)

Table 6: Summary estimates of power based on 17 studies providing 66 estimates of the relationship between changes in speed and changes in road safety

		Summary estimates of power			
Category	Number of estimates	Fixed-effects model	Random-effects model	Simple mean (not weighted)	Median (not weighted)
Fatal accidents	6	1.65	2.87	5.08	3.95
Serious injury accidents	6	1.89	3.61	20.42	4.64
Slight injury accidents	6	1.50	3.47	6.41	5.23
Injury accidents (unspecified)	16	1.22	2.55	5.77	2.47
Fatalities	11	3.43	3.58	10.88	5.50
Seriously injured road users	7	1.29	3.72	14.18	7.02
Slightly injured road users	7	1.41	2.92	8.82	4.32
Injured road users	3	3.44	3.62	6.78	3.69
Property-damage-only	4	2.79	4.25	2.49	4.21

Source: TØI-report 1034/2009

As can be seen from Table 6, the summary estimates of power vary considerably depending on how they were obtained. From a methodological point of view, the random-effects summary estimates are best. These estimates do not display the accident- or injury severity gradient predicted by the Power Model. In most categories, however, the number of estimates is quite low and the large heterogeneity observed makes all summary estimates uncertain.

3.5 Conclusions

It is concluded that the evidence provided by the update is too limited by itself to justify a revision of the Power Model. It was decided to pool evidence from the original study and the update into a consolidated data base for analysis. The analyses based on the pooled data base are presented in the next chapter.

4 Synthesis of new studies and 2004-studies

4.1 A consolidated data base

In order to gain a better foundation for analysis, the data used in 2004-study were merged with the new studies, forming a consolidated data base. This data base consists of 115 studies that present 526 estimates of the relationship between speed and road safety. In this chapter, results of analyses using the consolidated data base will be presented. First, main results based on a conventional meta-analysis are presented and compared to the results of the 2004 study. Then, more detailed results based on conventional meta-analysis are presented. Finally, the results of a meta-regression analysis are presented.

The consolidated data base does not contain all variables that were coded in the original study. Analyses indicated that many of these variables were not significant. Hence, the consolidated data base is limited to the following variables (in addition to study identification):

1. Publication year
2. Country of origin
3. Traffic environment (all, freeways, rural, urban, residential)
4. Accident or injury severity (fatal, serious, slight, unspecified injury)
5. Speed before (km/h)
6. Speed after (km/h)
7. Possible presence of regression-to-the-mean bias in study (yes or no)
8. Possible presence of long term trend bias in study (yes or no)
9. Possible presence of traffic volume bias in study (yes or no)
10. Possible presence of other risk factor bias in study (yes or no)

As in the original study, study quality is indicated by number of potential biases present in a study. Studies in which all the four potential sources of bias can be ruled out have the highest quality.

4.2 Main results

Table 7 presents the main results of the analysis of the consolidated database.

Table 7: Relationship between changes in speed and changes in road safety. Summary estimates of power based on 115 studies providing 526 estimates of the relationship

		Summary estimates of power			
Category	**Number of estimates**	**Fixed-effects model**	**Standard error**	**Random-effects model**	**Standard error**
Fatal accidents	53	3.89	0.30	3.84	0.56
Serious injury accidents	23	1.52	0.17	1.50	0.31
Slight injury accidents	23	1.17	0.07	1.08	0.17
Injury accidents (unspecified)	238	2.23	0.06	2.16	0.17
Fatalities	41	4.45	0.12	4.37	0.28
Seriously injured road users	21	1.45	0.13	2.64	0.51
Slightly injured road users	19	1.49	0.08	1.09	0.11
Injured road users	18	2.78	0.03	2.67	0.19
Property-damage-only	90	0.79	0.05	1.92	0.24

Source: TØI-report 1034/2009

With few exceptions, the results based on the random-effects model are close to those based on the fixed-effects model. The exceptions are the estimates of power for seriously injured road users and for property-damage-only accidents, both of which are considerably higher in the random-effects model than in the fixed-effects model.

The results are only partly consistent with the Power Model. Summary estimates of power are, as predicted by the Power Model, higher for fatalities and injured road users than for fatal accidents or injury accidents at all levels of severity. Moreover, estimates of power decline monotonically as accident- or injury severity is reduced from fatal to serious to slight. However, one would expect the estimate of power for serious accidents or injuries to be higher than that for all injury accidents, which is not the case. One would also expect the estimate of power for slight injury accidents or slight injuries to be lower than that for all injury accidents (severity not stated). This is the case, but the difference is surprisingly large in view of the fact that most injury accidents, or most injuries, are slight. One would therefore expect the estimate of power for slight injury accidents or slight injuries to be only slightly lower than the estimates for all injury accidents or all injured road users (severity not stated).

There are therefore certain anomalies in the results, as pointed out by Cameron and Elvik (2008). The results presented in Table 7 are not very different from the results of the original study. Table 8 compares the original results to those based on the consolidated database. All summary estimates of power presented in Table 8 are based on a random-effects model. All studies have been included.

The overall pattern in the findings is very similar. All summary estimates of power that apply to accidents are more precise in the consolidated data base than in the original study, as indicated by the smaller standard errors. Most of the summary estimates that refer to road users are also more precise in the consolidated database, but there are two exceptions: standard errors have increased for fatalities and seriously injured road users.

Table 8:The relationship between speed and road safety. Comparison of results of original study to results based on consolidated data base

	Summary estimates of power					
	Original study			Consolidated database		
Category	**Number of estimates**	**Best estimate**	**Standard error**	**Number of estimates**	**Best estimate**	**Standard error**
Fatal accidents	47	4.21	0.68	53	3.84	0.56
Serious injury accidents	17	1.35	0.34	23	1.50	0.31
Slight injury accidents	17	0.90	0.31	23	1.08	0.17
Injury accidents (all)	222	2.76	0.30	238	2.16	0.17
Fatalities	30	4.90	0.16	41	4.37	0.28
Seriously injured road users	14	1.59	0.27	21	2.64	0.51
Slightly injured road users	12	1.64	0.30	19	1.09	0.11
Injured road users (all)	15	1.78	1.60	18	2.67	0.19
Property damage only	86	1.70	0.54	90	1.92	0.24

Source: TØI-report 1034/2009

There are no consistent changes in the summary estimates of power. Some of these estimates are larger in the consolidated database than in the original study, some are smaller. The range appears to have narrowed. In the original study, the estimates of power ranged from 0.90 to 4.90. In the consolidated database, the range is from 1.08 to 4.37.

As noted before, the pattern seen in Table 8 is only partly consistent with the Power Model. A more detailed analysis will therefore be made to explore the consistency of the estimates of power. This chapter will consider variation in summary estimates of power with respect to traffic environment. Chapter 5 deals with issues related to study quality, initial speed, and speed variance.

4.3 Traffic environment as a moderator variable

All the re-analyses discussed in Chapter 2 suggested that the relationship between speed and road safety is moderated by the traffic environment. In order to test this, summary estimates of power have been developed for different traffic environments. Table 9 presents the estimates based on conventional meta-analysis. All summary estimates presented in Table 9 are based on at least two results. If only a single estimate of power is available, it is not presented.

Table 9 clearly shows the problems encountered when breaking down the data set into so many categories. In most cells of the table, only a few results form the basis of the summary estimate of power. For five cells of the table, there was only one, or no, estimate. There is clearly a lot of noise in the summary estimates presented in Table 9. Despite this, a pattern can be seen. There is a clear tendency for all estimates of power to be lower for residential areas than for the other types of traffic environment. A somewhat less consistent tendency can be seen for estimates of power for urban areas to be lower than those for freeways (motorways) and rural areas. On the whole, therefore, Table 9 gives some support to the hypothesis that the type of traffic environment moderates the effect of speed on road safety.

Table 9: Summary estimates of power by traffic environment, random effects model

	Summary estimates of power (standard error) [N]			
Category	**Freeways**	**Rural roads**	**Urban roads**	**Residential**
Fatal accidents	4.44 (1.22) [12]	4.01 (0.74) [30]	4.68 (2.15) [5]	1.76 (1.41) [5]
Fatalities	4.50 (0.36) [15]	4.67 (0.49) [20]	3.87 (1.81) [4]	No estimate
Serious injury accidents	No estimate	2.62 (2.72) [3]	4.62 (1.40) [9]	1.31 (0.32) [7]
Seriously injured road users	4.94 (2.94) [4]	3.60 (1.09) [9]	3.08 (1.01) [5]	1.87 (0.73) [2]
Slight injury accidents	No estimate	1.06 (0.55) [4]	4.37 (0.74) [9]	0.87 (0.19) [7]
Slightly injured road users	3.45 (2.72) [4]	1.33 (0.47) [8]	3.41 (0.87) [4]	1.04 (0.11) [2]
Injury accidents (unspecified)	2.96 (0.76) [17]	3.40 (0.43) [107]	1.51 (0.27) [92]	1.82 (0.42) [20]
Injured road users (unspecified)	2.66 (0.19) [8]	3.18 (1.90) [8]	No estimate	No estimate
Property damage only	2.27 (1.20) [13]	2.79 (0.90) [26]	0.41 (0.67) [42]	0.97 (0.40) [6]

Source: TØI-report 1034/2009

In order to gain a clearer picture, the analysis was simplified by merging freeways and rural roads and by merging urban roads and residential areas. There are then only two categories for traffic environment, which will be referred to as rural and urban. Table 10 shows the results of the analysis.

Table 10: Summary estimates of power by simplified coding of traffic environment

	Summary estimates of power (standard error)	
Category	**Rural and freeway**	**Urban and residential**
Fatal accidents	4.13 (0.63)	2.64 (1.18)
Fatalities	4.56 (0.29)	3.87 (1.81)
Serious injury accidents	2.62 (2.72)	1.48 (0.32)
Seriously injured road users	3.76 (1.02)	2.29 (0.59)
Slight injury accidents	1.06 (0.55)	1.08 (0.18)
Slightly injured road users	1.39 (0.46)	1.08 (0.11)
Injury accidents (unspecified)	3.30 (0.37)	1.60 (0.23)
Injured road users (unspecified)	2.66 (0.19)	No estimate
Property damage only	2.60 (0.72)	0.82 (0.35)

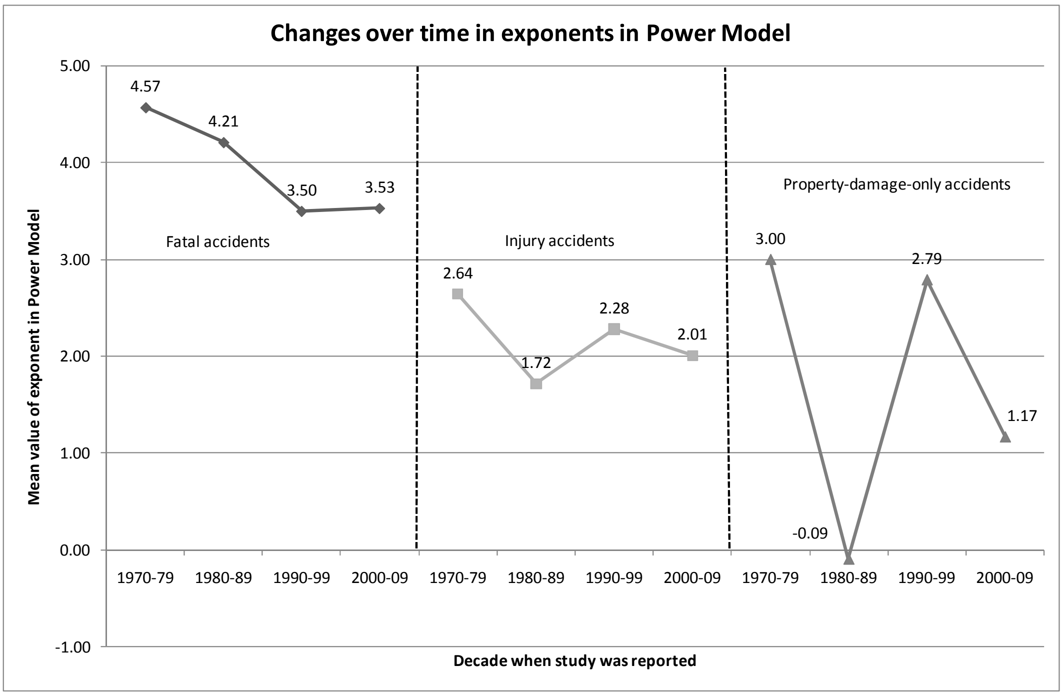
Source: TØI-report 1034/2009

The pattern in Table 10 is more systematic than in Table 9. There is a clear tendency for estimates of power to be higher for rural traffic environments than for urban traffic environments. The type of traffic environment is therefore a moderator for the effect of speed on accidents.

The estimates presented in Table 10 do not, however, control for the other independent variables represented in the data. In order to control for these variables, a meta-regression analysis was run.

4.4 The stability of exponents over time

Figure 1 shows mean estimates of the exponents in the Power Model for fatal accidents, injury accidents and property-damage-only accidents according to the decade in which studies were published. There were too few studies to estimate exponents for the decade 1960-1969.



Source: TØI-report 1034/2009

Figure 1: Mean estimates of exponents in Power Model according decade when studies were published

In Figure 1, no distinction is made between different traffic environments; the estimated exponents apply to all traffic environments. A tendency is seen for the exponents to decline over time. The results for injury accidents and, in particular, property-damage-only accidents are somewhat erratic, but the long-term trend is nevertheless clear.

A decline in the value of the exponents means that the effects on accidents of given changes in speed have become smaller (i.e. a 10 % reduction in speed had a greater effect on fatal accidents in the 1970's than it does now). As far as fatal accidents are concerned, it is perhaps not surprising that the effects of speed have diminished over time. New safety devices like seat belts, air bags, collapsible steering columns, crash helmets, improved guard rails, etc. imply that accidents that were fatal 30-40 years ago are often survivable today. Some of these safety devices have also reduced the probability of getting injured in an accident of a given severity, and have thus also weakened the effect of changes in speed on injury accidents.

The results for property-damage-only accidents are very erratic, and it is difficult to think of reasons why speed should matter less for property-damage-only accidents today than it did 30-40 years ago. It is more likely that the results are influenced by poor data and poor control of potentially confounding factors.

4.5 Meta-regression analysis

4.5.1 Models developed

A total of six models were developed in the meta-regression analysis. The six models were:

1. The country model
2. The accident- or injury severity model
3. The study quality model
4. The traffic environment model
5. The year of publication model
6. The initial level of speed model

The models were developed stepwise, meaning that model 2 contains all variables included in model 1, model 3 contains all variables included in model 2, etc. Model 6 is the most extensive model and includes all variables included in models 1 through 5 in addition to a variable representing initial speed.

The country model (model 1) consisted of a constant term and 11 dummy variables representing countries in which the studies were made. Norway was used as reference country. This model was developed for exploratory purposes only. The chief purpose of developing this model was to test whether the results varied between countries. Significant coefficients for the country variables indicates that the effects of speed varies between countries, which does not seem very plausible. Only one of the country variables was statistically significant at the 5 % level; the other ten were far from statistically significant. Since, by chance alone, it would not be surprising if one out of eleven variables happened to be significant, it was concluded that the results of the main analyses can be generalised across countries.

The accident- or injury severity model (model 2) was also mainly intended for exploratory purposes. The model included a constant term, 11 dummy variables representing countries and 8 variables representing different levels of accident- or injury severity. The constant term in this model represented property-damage-only accidents. The chief purpose of this model was to test whether the coefficients for accident- or injury severity were of roughly the same magnitude and displayed roughly the same pattern as in the conventional meta-analysis. This test was intended as a check that no grave errors had been made in developing and running the meta-regression model. The coefficients were found to display a meaningful pattern.

The study quality model (model 3) included four variables representing the potential presence of regression-to-the-mean, lack of control for long-term trend, lack of control for traffic volume, and lack of control for other confounding risk factors in a study. These four variables were coded as 1 if a source of error was judged to be present in a study, 0 if the source of error was judged not to be present in a study. In addition, the model included all variables that were included in model 2 (the accident- or injury severity model). The results of the study quality model are presented in section 5.1.

The traffic environment model (model 4) included, in addition to all variables included in model 3, four variables representing traffic environment. Urban roads were used as reference category and dummy variables represented the other traffic environments. Results based on this model are presented in section 4.5.2.

The publication year model (model 5) included year of publication in addition to all variables included in model 4 (the traffic environment model). When developing estimates of power based on this model, year of publication was set to 2009. Results based on this model are presented in section 4.5.2.

Finally, the initial level of speed model (model 6) included initial speed in kilometres per hour in addition to all variables included in model 5. This model was the most comprehensive of all models and a total of 30 coefficients were estimated in this model. Results are presented in section 4.5.2.

4.5.2 Results of meta-regression analyses

As noted in Chapter 2, two main topics were focused in the re-analyses of the 2004-study: the moderating effect of traffic environment and the importance of initial speed. The results presented here will focus on the moderating effects of traffic environment, whereas initial speed will be discussed in section 5.2.

The two topics are, however, closely related and difficult to separate, since initial speed depends on the traffic environment and varies systematically between different types of traffic environment. There is, in other words, a risk both that the variables will be co-linear in a meta-regression model, and that model estimates derived by applying coefficients both for traffic environment and initial speed will involve a double counting of effects. Hence, estimates of power have been developed both by applying the traffic environment variables only, by applying the initial speed variable only, and by applying both sets of variables.

Table 11 shows estimates of power based on five different models that include variables denoting traffic environment. These models are:

1. The traffic environment model (model 4). This model includes variables for type of traffic environment, but not year of publication and not initial speed.
2. The publication year model (model 5). This model includes year of publication in addition to the traffic environment variables. By comparing estimates based on this model to those based on the traffic environment model (model 4), it is possible to assess whether the effects of speed have changed over time, since year of publication was set to 2009 in the publication year model, whereas the estimates in model 4 represent the mean year of publication for all studies, which was 1991.
3. The initial level of speed model (model 6), version A. This model includes all variables included in model 5 and a variable representing the mean speed of traffic before a change took place. Estimates of power were developed by applying the coefficients both for type of traffic environment and for initial mean speed.

4. The initial level of speed model (model 6), version B. In this version, the coefficient for initial speed was disregarded and only the coefficients applying to different types of traffic environment were used. The reason, as stated above, is that initial speed and type of traffic environment are highly correlated.
5. The initial level of speed model (model 6), version C. In this version, the traffic environment variables were disregarded and only the initial level of speed variable used. The reason was the same as stated above: the mean speed of traffic varies greatly between different types of traffic environment.

Before presenting and discussing the results of analysis, an important difference between the meta-regression analysis and the conventional meta-analysis should be noted. In the meta-regression analysis, traffic environment has been entered as a coded variable, with the following values: all roads, freeway, rural road, urban road, residential road. The first of these categories, all roads, has been coded for those studies that did not state which traffic environment results applied to, or stated that they applied to all types of traffic environment.

In the conventional meta-analysis, on the other hand, the category "all types of traffic environment" is the sum of all estimates applying to the different types of traffic environment, i.e. it comprises the entire data set. In the meta-regression analysis, there were 14 observations for all types of traffic environment, 74 for freeways, 207 for rural roads, 171 for urban roads and 51 for residential roads.

The results presented in Table 11 shows that the best estimates of power vary both between the five different models and between the five different types of traffic environment included. In general, powers are higher for all roads, freeways, and rural roads than for urban roads and residential roads. This confirms the results of the conventional meta-analysis, as reported in Tables 9 and 10.

The main tendencies are the same for all types of traffic environment. The highest estimates of power are found for fatal accidents and fatalities. The estimated exponents are smaller for serious injury accidents and seriously injured road users and still smaller for slight injury accidents and slightly injured road users. This pattern is consistent with the Power Model. The estimates for injury accidents of unspecified severity are close to those for serious injury accidents, whereas the estimates for injured road users (injury severity not specified) are closer to those for slightly injured road users.

There are no glaring anomalies in the results based on models 4, 5 and 6A for all roads, freeways and rural roads. The powers estimated by means of model 6B are implausibly high, whereas the powers estimated by means of model 6C are much lower and in some cases even negative. Negative powers must be regarded as very implausible. A negative power suggests that the number of accidents goes down when speed increases. This is inconsistent with the data and with the results of the conventional meta-analysis.

Table 11: Results of meta-regression analysis. Summary estimates of power according to model and type of traffic environment. Models explained below table

	Summary estimates of power					
Accident- or injury severity	**Model 4**	**Model 5**	**Model 6A**	**Model 6B**	**Model 6C**	**Mean**
All traffic environments (N = 14)						
Fatal accidents	2.42	2.79	2.43	4.74	0.40	2.56
Fatalities	2.97	3.46	3.05	5.36	1.02	3.17
Serious injury accidents	1.38	1.64	1.28	3.58	-0.76	1.42
Seriously injured road users	2.23	2.54	2.14	4.44	0.10	2.29
Slight injury accidents	0.87	1.14	0.81	3.11	-1.23	0.94
Slightly injured road users	0.85	1.06	0.68	2.99	-1.35	0.85
Injury accidents (unspecified)	1.43	1.85	1.49	3.79	-0.55	1.60
Injured road users (unspecified)	1.12	1.52	1.15	3.45	-0.89	1.27
Property damage only	0.52	0.88	0.54	2.84	-1.50	0.66
Freeways (N = 74)						
Fatal accidents	2.85	3.66	3.58	6.81	-0.53	3.28
Fatalities	3.40	4.34	4.20	7.43	0.09	3.89
Serious injury accidents	1.81	2.52	2.42	5.65	-1.69	2.14
Seriously injured road users	2.66	3.42	3.28	6.51	-0.82	3.01
Slight injury accidents	1.30	2.02	1.95	5.18	-2.15	1.66
Slightly injured road users	1.28	1.94	1.83	5.06	-2.28	1.57
Injury accidents (unspecified)	1.86	2.73	2.64	5.87	-1.47	2.32
Injured road users (unspecified)	1.55	2.40	2.30	5.53	-1.81	1.99
Property damage only	0.95	1.76	1.68	4.91	-2.42	1.38
Rural roads (N = 207)						
Fatal accidents	3.39	4.20	4.29	6.97	0.02	3.77
Fatalities	3.94	4.87	4.91	7.59	0.65	4.39
Serious injury accidents	2.34	3.05	3.13	5.81	-1.13	2.64
Seriously injured road users	3.20	3.95	3.99	6.67	-0.27	3.51
Slight injury accidents	1.83	2.55	2.66	5.34	-1.60	2.16
Slightly injured road users	1.82	2.47	2.54	5.22	-1.72	2.07
Injury accidents (unspecified)	2.40	3.26	3.35	6.03	-0.92	2.82
Injured road users (unspecified)	2.09	2.93	3.01	5.69	-1.26	2.49
Property damage only	1.49	2.29	2.54	5.07	-1.87	1.88
Urban roads (N = 171)						
Fatal accidents	0.53	0.96	0.91	2.70	0.91	1.28
Fatalities	1.08	1.64	1.53	3.32	1.53	1.89
Serious injury accidents	-0.51	-0.18	-0.25	1.54	-0.25	0.15
Seriously injured road users	0.35	0.72	0.62	2.41	0.62	1.02
Slight injury accidents	-1.02	-0.69	-0.71	1.08	-0.71	-0.33
Slightly injured road users	-1.04	-0.77	-0.84	0.95	-0.84	-0.42
Injury accidents (unspecified)	-0.45	0.03	-0.03	1.76	-0.03	0.32
Injured road users (unspecified)	-0.77	-0.30	-0.37	1.42	-0.37	-0.01
Property damage only	-1.37	-0.95	-0.98	0.81	-0.98	-0.62
Residential roads (N = 51)						
Fatal accidents	0.80	1.08	1.26	2.58	1.38	1.42
Fatalities	1.35	1.76	1.88	3.21	2.00	2.04
Serious injury accidents	-0.24	-0.06	0.10	1.43	0.22	0.29
Seriously injured road users	0.61	0.84	0.97	2.29	1.08	1.16
Slight injury accidents	-0.75	-0.56	-0.36	0.96	-0.25	-0.19
Slightly injured road users	-0.77	-0.65	-0.49	0.84	-0.37	-0.29
Injury accidents (unspecified)	-0.19	0.15	0.32	1.64	0.44	0.47
Injured road users (unspecified)	-0.50	-0.18	-0.02	1.30	0.10	0.14
Property damage only	-1.10	-0.82	-0.63	0.69	-0.52	-0.48

Source: TØI-report 1034/2009

Model 4 = type of traffic environment; Model 5 = type of traffic environment + year of publication; Model 6A = type of traffic environment + year of publication + initial speed; Model 6B = like 6A, but without initial speed; Model 6C = like 6A, but without type of traffic environment (replaced by mean initial speed per environment)

Mean estimates based on all five models have been developed. These estimates are by and large plausible for all roads, freeways and rural roads. The estimates of power are highest for rural roads, slightly lower for freeways. This is plausible, since freeways have been designed for travel at high speeds and very many of the hazards that can be found on all-purpose rural roads have been removed from freeways. Sharp and surprising curves, steep hills, at-grade junctions, slow-moving agricultural vehicles and the occasional pedestrian or cyclist are traffic hazards that are found on rural roads, but not on freeways.

The data confirm that the mean speed of traffic varies between traffic environments. Initial mean speed was 104.3 km/h on freeways, 86.5 km/h on rural roads, 74.4 km/h on all roads, 57.8 km/h on urban roads and 42.7 km/h on residential roads. The estimates of power for urban roads and residential roads seem less plausible than those for all roads, freeways and rural roads. Except for the estimates based on model 6B, negative powers are quite common. The high frequency of negative estimates of power is unlikely to be correct. Only 125 of the 526 (23.8 %) estimates of power that serve as the basis for analysis are negative; these estimates contribute only 5.7 % of the fixed-effects statistical weights (i.e. they originate to a large extent from small studies, the results of which are highly uncertain). Yet, out the 90 estimates of power for urban roads and residential roads based on the five models presented in Table 11, 41 (45.6 %) are negative. This suggests that there must be a methodological explanation for the large number of negative estimates of power.

There are three versions of model 6. The most comprehensive is model 6A; it includes all explanatory variables. Model 6B omits the initial speed variable, but retains the dummy variables for types of traffic environment. Model 6B produces higher estimates of power than the other models. Model 6C omits the dummies for type of traffic environment, but retains the speed variable. The coefficient for initial speed is negative. This means that inclusion of this variable in a model will lower the estimates of power – the more so the higher the initial level of speed. The coefficients for type of traffic environment are, with a single exception, positive and will therefore influence estimates of power in the opposite direction of the speed variable. The variables are highly correlated; hence estimates of power vary greatly depending on which of these variables are included in the model.

Unfortunately, there is no satisfactory solution to this problem. Omitting one of the highly correlated variables will not solve the problem; the omitted variable lurks in the background and influences estimates all the same, creating omitted variable bias. As far as the estimates of power for urban and residential roads are concerned, meta-regression analysis was not very successful and greater trust should be placed in the estimates based on the conventional meta-analysis.

4.6 Conclusions

The main findings of the analyses presented in this chapter can be summarised as follows:

1. The Power Model of the relationship between changes in the mean speed of traffic and changes in road safety is broadly speaking supported. Traffic environment is, however, an important moderating variable and separate estimates of power should be developed for freeways and rural roads on the one hand, and urban and residential roads on the other hand.
2. The exponents representing the effects of speed appear to have been slightly reduced over time. Speed nevertheless remains a very powerful risk factor for accidents and injuries.
3. Meta-regression analysis shows that the Power Model can be applied in all countries. There is no support for the idea of developing separate versions of the model for each country. This shows that the effects of speed on road safety are likely to be universal and not strongly influenced by conditions that are specific to a certain country.
4. Meta-regression analysis was only partly successful in refining the estimates of power for various traffic environments. The findings for all roads, freeways and rural roads make sense and are not very different from the findings of the conventional meta-analysis. The findings for urban and residential roads are less convincing and show an unexpectedly large number of negative values for the exponents. While negative exponents are found in the data, they are not common and contribute to only 5.7 % of the statistical weights assigned to the estimates.
5. Examination of the coefficients in the meta-regression analysis suggests that the anomalous findings for urban and residential roads are likely to be attributable to a high correlation between initial speed and variables representing different types of traffic environment. There is, unfortunately, no very good solution to this problem of co-linearity among the explanatory variables.
6. The possible dependence of estimates of power on initial speed is discussed in Chapter 5.

5 Analysis of selected topics

In this chapter, some topics that have been discussed in recent studies of the relationship between speed and road safety will be discussed in greater detail. The topics covered include: Study quality; the importance of initial speed for the impact of changes in speed; the relationship between individual driver speed choice and accident involvement rate and the relationship between speed variance and road safety.

5.1 Study quality

Study quality is indicated by the possible presence of up to four sources of confounding:

1. Regression-to-the-mean
2. Long-term trends
3. Changes in traffic volume
4. Risk factors associated with speed

If none of these factors are present in a study, it gets the highest score for quality. Studies that have up to three potential sources of confounding have been included. Studies that were judged to be afflicted by all four potential sources of confounding were not included. Table 12 shows mean estimates of power, depending on the number of sources of error present in a study. To avoid cluttering the table, standard errors are not shown. It should be noted, however, that many estimates are highly uncertain.

As far as the results of the conventional meta-analysis are concerned, the pattern is untidy. In some cases, notably for injury accidents, a tendency is seen for estimates based on poor studies to be higher than estimates based on good studies. However, such a pattern is not seen for injured road users, nor for other levels of accident- or injury severity.

Estimates of power based on meta-regression were developed on the basis of model 3 (see chapter 4 for a description of this model). This model was preferred because it gives the most conservative estimates of the effects of lack of control for the potentially confounding variables and is therefore not likely to overstate the influence of poor study quality on study findings. Estimates of power were developed by defining all logically possible combinations of 1, 2 or 3 sources of error and weighting the estimates in proportion to the inverse value of the square of the standard errors of the coefficients (i.e. weight = $1/SE^2$).

Table 12: Mean estimates of power as a function of the number of potential sources of confounding in a study. Estimates based on conventional meta-analysis and on meta-regression

	Mean estimates of power by number of sources of potential confounding – random effects model			
Accident or injury severity	**0**	**1**	**2**	**3**
	Estimates based on conventional meta-analysis			
Fatal accidents	3.47	3.64	7.82	3.33
Fatalities	4.66	1.73	4.10	----
Serious injury accidents	1.18	1.96	2.11	1.03
Seriously injured road users	3.04	2.37	2.83	----
Slight injury accidents	1.05	1.65	1.23	0.73
Slightly injured road users	1.35	1.08	0.31	----
Injury accidents – not further specified	1.97	2.02	2.18	3.33
Injured road users – not further specified	2.75	1.40	2.22	2.59
Property-damage-only accidents	0.41	3.87	2.53	1.06
	Estimates based on meta-regression			
Fatal accidents	2.79	2.92	3.66	4.39
Fatalities	3.13	3.26	3.99	4.73
Serious injury accidents	1.27	1.39	2.13	2.87
Seriously injured road users	2.20	2.32	3.06	3.79
Slight injury accidents	0.77	0.90	1.63	2.37
Slightly injured road users	0.93	1.05	1.79	2.53
Injury accidents – not further specified	1.71	1.83	2.57	3.31
Injured road users – not further specified	1.33	1.46	2.20	2.93
Property-damage-only accidents	0.71	0.84	1.58	2.32

Source: TØI-report 1034/2009

The results of the meta-regression analysis are more consistent than the results of the conventional meta-analysis. Meta-regression shows that mean estimates of power increase considerably when studies fail to control for potentially confounding variables. This tendency is consistent with other studies (Elvik 1997, Erke 2009) which show that poorly controlled studies tend to give inflated estimates of the effects of road safety measures.

5.2 The importance of initial speed

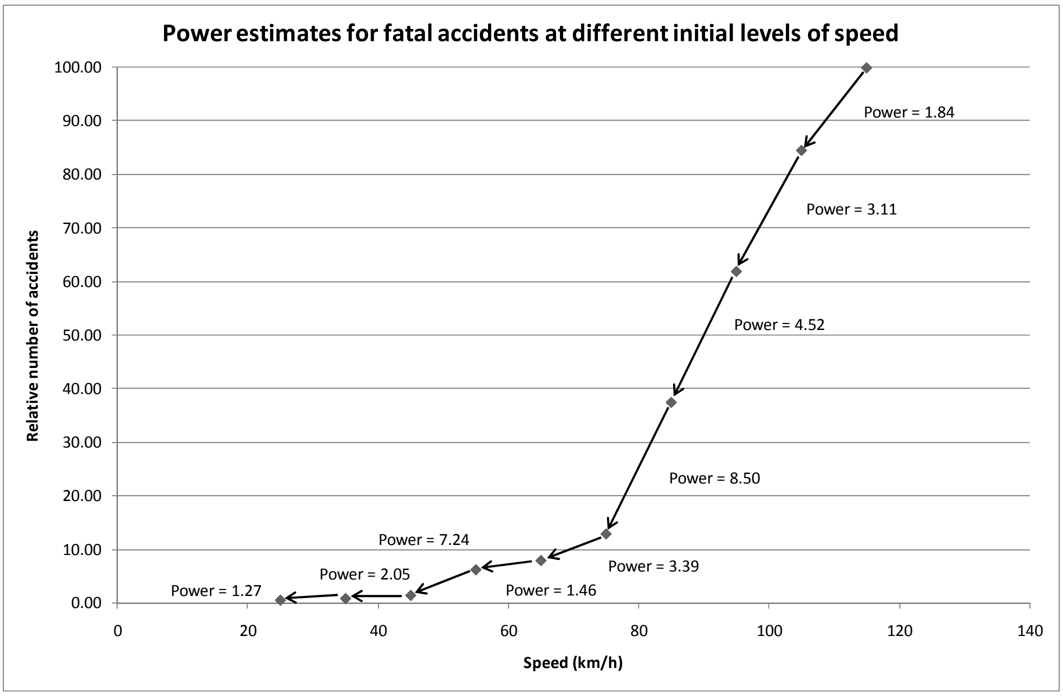
The re-analyses of Hauer and Bonneson indicated that the effects on accidents or injuries of changes in speed depend on initial speed. To test whether the data support this, mean estimates of power were developed for the following levels of initial speed: > 110 km/h; 100-109.9 km/h; 90-99.9 km/h; 80-89.9 km/h; 70-79.9 km/h; 60-69.9 km/h; 50-59.9 km/h; 40-49.9 km/h; 30-39.9 km/h and < 30 km/h. A sufficient number of data points to stratify results this way exists only for fatal accidents and injury accidents (and for property damage only accidents, but these data are regarded as too noisy and less interesting).

Figure 2 shows results for fatal accidents. Changes in speed have been stated as changes of 10 km/h (from 115 to 105 km/h; 105 to 95 km/h, etc). Mean estimates of power have been used at each interval to create the data points shown in the figure. The data point to the upper right has been given the value of 100, so that changes can be interpreted as percentage changes in the number of accidents.

The data points have been created as follows: For initial speeds above 110 km/h, the mean estimate of power, applying a random effects model was found to be 1.843. Initial speed was set to 115 km/h, final speed to 105 km/h. The estimated reduction of the number of fatal accidents associated with this speed reduction is:

$$\text{Estimated reduction of fatalities} = \left(\frac{105}{115}\right)^{1.843} = 0.8456 \tag{3}$$

The number of fatal accidents is expected to be reduced to 0.8456 times the initial value. The number of fatalities at an initial speed of 115 km/h is set to 100 (upper right data point in Figure 2); once speed is reduced to 105 km/h, the new data point is (105, 84.56; the second data point in Figure 2 at the bottom of the arrow starting at the first data point). The process is repeated for a speed changes from 105 to 95 km/h; the estimate of power is 3.107; applying this estimate, it can be worked out that the number of fatal accidents is expected to be reduced from 84.56 to 61.96. Continuing this way down to an initial speed of 35 km/h, the curve in Figure 2 was derived.



Source: TØI-report 1034/2009

Figure 2: The dependence of the effects on fatal accidents of changes in speed from different initial levels

As can be seen, the estimates of power differ according to initial speed. The value of the exponent is lower at both ends of the distribution than in the middle. This is consistent with a logistic function.

The results for injury accidents did not indicate that summary estimates of power varied systematically according to initial speed. The overall conclusion is that the data give limited support to the hypothesis that the effects on road safety of changes in speed depend on the initial level of speed. It is, however, reasonable to assume that the relationship between impact speed – as opposed to the speed of traffic – and accident severity is best described by a logistic function (see e.g. U.S. Department of Transportation 2005).

The meta-regression analysis, whose main findings were reported in chapter 4, found a negative coefficient for initial speed. This means that the higher the initial speed, the lower the estimate of power, all else equal. This finding is implausible and is probably attributable to confounding caused by co-linearity between initial speed and type of traffic environment.

5.3 Individual speed choice and accident involvement

The relationships examined by means of the Power Model and revisions of that model all apply to the effects of changes in the mean speed of traffic on the total number of accidents or injured road users. These model say nothing about the relationship between the speed chosen by an individual driver and the accident rate of that driver. In a review of studies of the relationship between driving speed and road safety, Aarts and van Schagen (2006) summarise the results of studies that have estimated functions describing the relationship between individual speed and individual accident rate.

Their review present results of five studies; however a function describing the relationship between speed and accident rate is presented only for four of these studies. All these functions model individual accident rate as a function of the deviation between the speed of each vehicle and the mean speed of traffic. Unfortunately, this way of representing the relationship between speed and accident involvement can give rise to spurious findings, as will be discussed more in detail in the next section. The four functions presented by Aarts and van Schagen give very different results, suggesting that they are influenced by confounding factors.

It must therefore be concluded that the relationship between individual speed and individual accident rate is not well known at the present. An interesting study of speed as a measure of driver risk was made by Wasielewski (1984). Figure 3 presents the relationship found between individual speed (measured at least twice for each driver) and the number of accidents recorded for a driver.

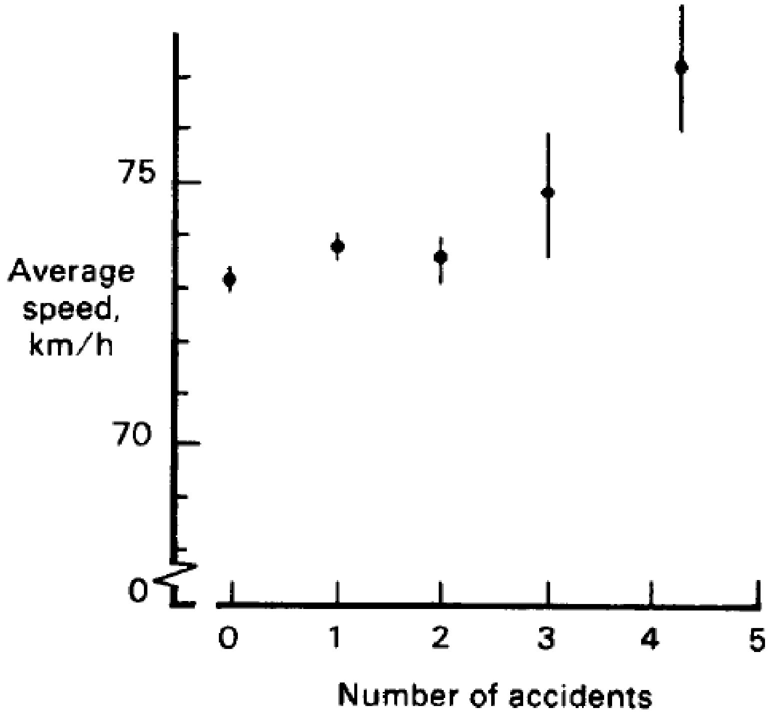


Figure 3: Relationship between individual mean speed and number of accidents per driver. Based on Wasielewski 1984 (figure 6 in original paper)

In the case-control studies reviewed by Aarts and van Schagen (2006), the sample of drivers was different for the case- and control groups. A group of drivers involved in accidents was compared to a different group of drivers observed in traffic. Wasielewski, on the other hand, made sure that speed data and accident data referred to the same drivers. This approach eliminates a major source of confounding. Moreover, Wasielewski indirectly controlled for differences in driving distance by observing cars in traffic, since the probability of observing a car in traffic is higher the more often the car is driven.

A study that indirectly sheds light on the relationship between speed and accident involvement is a study by Cooper (1997) on the relationship between convictions for speeding and the number of crashes recorded per driver in official driver records. He found the following relationship:

Number of convictions for speeding	Number of crashes per driver
0	0.198
1	0.179
2	0.325
3	0.432
4+	0.599

As is seen, the mean number of accidents per driver increases as the number of convictions for speeding increases. However, the study did not control for annual driving distance. It is reasonable to assume that a high annual driving distance is associated both with an increased probability of detection for speeding and an increased chance of becoming involved in an accident. Thus, if driving distance had been known, different results might have been obtained.

5.4 The importance of speed variance

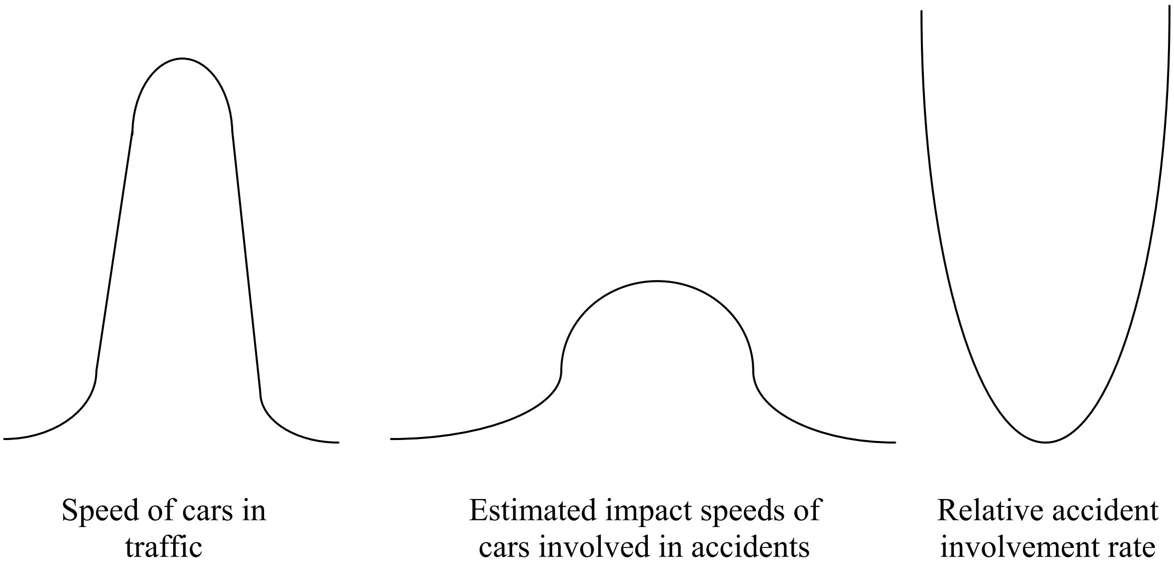
The importance of speed variance for the number of accidents has been discussed at great length. This discussion was started by studies reported by Solomon (1964), Munden (1967) and Cirillo (1968), suggesting that drivers who drove slower or faster than the mean speed of traffic were more often involved in accidents than drivers who deviated less from the mean speed of traffic. Hauer (1971) provided a theoretical explanation of the U-shaped relationship between speed and accident involvement in terms of the frequency of overtaking. Applying traffic flow theory, he showed that slower vehicles are overtaken more often than faster vehicles, and that the fastest vehicles overtake other vehicles more often than slower vehicles. Overtaking another vehicle is likely to increase the risk of accident.

West and Dunn (1971) subsequently replicated the U-shaped relationship between speed and accident involvement, but their study found a considerably flatter relationship than previous studies. The study of West and Dunn was arguably more rigorous than previous studies, suggesting that the very marked U-curve found these studies could partly be an artefact.

White and Nelson (1970) proposed a methodological explanation of the U-shaped relationship between speed and accident involvement as early as 1970. Errors in speed measurements can generate a spurious U-shaped curve for the relationship between deviation from mean speed and relative rate of accident involvement. More specifically, reconstructing the speed of vehicles involved in accidents is likely to be associated with more uncertainty than measuring the speed of vehicles in traffic. This is shown in figure 4.

The speed of vehicles in traffic is assumed to be measured quite precisely and display an approximately normal distribution. The pre-crash speed of vehicles involved in accidents is likely to be estimated less precisely, showing a distribution with greater dispersion. Even if the risk of becoming involved in an accident was entirely independent of speed (which is, of course, highly implausible), a spurious U-shaped curve could arise if accident involvement rate is estimated by dividing the speed of vehicles involved in accidents by the speed of vehicles in traffic.

Another potential source of error is the precise definition of the accident involvement variable. If this variable is defined in terms of the number of cars involved in accidents, all accidents that involve two cars will be counted twice. Moreover, the study of Solomon (1964) included vehicles that had slowed down in order to make turns in junctions. Clearly, these vehicles were not travelling at their normal speed when they became involved in an accident.



Source: TØI-report 1034/2009

Figure 4: Imprecise reconstruction of speed of vehicles involved in accidents as source of a spurious relationship between speed and accident involvement

The analysis of White and Nelson went unnoticed for many years, until new studies of the relationship between individual speed and individual accident involvement were made in Australia (Kloeden et al. 1997, 2001). The studies of Kloeden et al. did not replicate the U-shaped relationship between speed and accident involvement found in previous studies. Accident involvement was found to increases monotonically as a function of speed. The relationship was best described by means of an exponential function, meaning that accident involvement increased at a faster rate the higher the speed of travel.

The studies of Kloeden et al. were, however, case-control studies just like the first studies that were made to assess the relationship between individual speed and accident involvement, and were therefore subject to the same methodological weaknesses. Commenting on these studies, Hauer (2004) remarked:

"An important weakness of the case-control approach is the possibility of confounding. The most commonly used defence against confounding is the matching of controls and cases; that is the selection of controls so that they match cases on potential confounding characteristics (such as age, gender, car mass and number of occupants). In [the reports by Kloeden et al.] there was no matching on the potential confounders of age, gender, car mass and number of occupants. Therefore the results … are vulnerable to plausible confounding."

The controversy regarding the role of speed variance in contributing to accidents was given a major impetus by a paper published by Lave (1985) in American Economic Review in 1985. Based on an analysis of a cross-section data set for states in the United States, Lave concluded that fatality rates were associated with speed variance, not the mean speed of traffic. The ensuing debate is described in vivid terms by Hauer (2005). His conclusion is that the interpretation given by Lave is most probably erroneous.

To see why, consider the fictitious data presented in Table 13. The data are intended to represent five states in which the mean speed of traffic is the same, but speed variance differs. In each state, half the drivers are slow, the other half are fast. The larger the difference between the slow drivers and the fast drivers, the greater is speed variance.

Table 13: Apparent effect of speed variance on fatality rate. Fictitious data

Slow drivers (50%)	Fast drivers (50%)	Mean speed	Variance	Fatality rate
58	62	60	8	13.05
56	64	60	32	13.31
54	66	60	72	13.74
52	68	60	128	14.35
50	70	60	200	15.13

Source: TØI-report 1034/2009

As can be seen, variance increases considerably as the difference in speed between the slow drivers and the fast drivers increases. Fatality rate was estimated as follows:

$$\text{Fatality rate} = \frac{\left[\left(\bar{V}_s^4\right)\cdot 0.5\right]+\left[\left(\bar{V}_f^4\right)\cdot 0.5\right]}{1{,}000{,}000} \qquad (4)$$

$\bar{V}_s$ and $\bar{V}_f$ are the mean speeds of the slow and fast drivers. Since the rate of fatal accidents is roughly proportional to the fourth power of speed, these mean speeds are raised to a power of 4 in order to estimate the fatality rate. Slow drivers and fast drivers both make up half the drivers; hence the estimate for each group is weighted by 0.5, and their fatality rates added to obtain the mean fatality rate for traffic. As can be seen, fatality rate increases as variance increases, but this is only because the fatality rate for the fast drivers increases more rapidly than for the slow drivers, because the exponent is more than 1. Thus the impression is created that fatality rate is related to speed variance, when in fact it is related to mean speed only, and both the slow drivers and the fast drivers are located on the same function relating speed to fatality rate, albeit at different points along this function.

There is, in other words, a distinct possibility that the apparent relationship between speed variance and safety is entirely spurious. Much along the same lines as the argument above, Davis (2002) shows that a positive correlation between accident rate and speed variance can be expected when individual accident rate is either an increasing, a decreasing or a U-shaped function of speed. Thus a correlation observed at an aggregate level between speed variance and accident rate provides no evidence about the relationship between speed and accident rate at an individual level.

5.5 Conclusions

The main findings of the analyses presented in this chapter can be summarised as follows:

1. There is a tendency for studies that do not control for a number of important potentially confounding factors to report higher estimates of power than studies that control for these factors. This tendency is not consistent in all subsets of the data, but is most clearly evident for injury accidents, which represent 238 of the 526 estimates included in this study.
2. A tendency is found for estimates of power referring to fatal accidents to depend on initial speed, suggesting that a logistic model may describe the relationship between speed and fatal accidents better than the power model. For injury accidents, estimates of power did not show any consistent relationship with initial speed.
3. The relationship between individual speed and individual accident involvement is not well known. Most studies that have investigated this relationship have relied on inappropriate study designs and potentially misleading functions to describe the relationship between speed and accident involvement. Despite this, it is reasonable to assume that those who drive fast are more often involved in accidents than those who drive more slowly.
4. The relationship between speed variance and accident rate has been discussed extensively. There is a very distinct possibility that almost all studies claiming that there is such a relationship have reported findings that are to a large extent spurious.

6 A restatement of the case for speed limits

Today, speed limits are almost universal. Although there are still sections on German Autobahns that do not have speed limits, speed limits are spreading even on these last remnants of a road system with no speed limits. It is taken for granted that there should be speed limits. It would therefore seem to be an anachronism to raise the question of why there should be speed limits and what the principal arguments for them are. This chapter gives a restatement of the case for speed limits. The case is based on a critical examination of driver rationality in speed choice. The argument is made that speed limits are needed to efficiently coordinate driver speed choice based on normative criteria of rationality, as there are reasons to believe that a "free" choice of speed would not produce outcomes that are optimal from a societal point of view.

6.1 Perspective and research problem

Despite the fact that speed limits have been introduced almost everywhere, they remain a bone of contention. Although most drivers appear to accept the need for speed limits, discussion continues about their level. Denmark recently raised the speed limit on some motorways from 110 to 130 km/h (Reiff et al. 2008). Are speed limits really needed? Why not leave the choice of speed to drivers? What are the principal arguments for regulating the choice of speed?

The choice of speed can be studied from several different perspectives. For the purpose of the analysis presented in this chapter, the perspective of normative economic welfare theory has been chosen. One reason for this choice is that normative welfare economics is based on a respect for citizen sovereignty (often referred to as consumer sovereignty in economic theory) and a principle of methodological individualism (i.e. the point of view that all social phenomena originate in individual behaviour and choices) (Adler and Posner 2001, 2006; Mishan and Quah 2007). In other words, the analysis is based on actual individual behaviour, e.g. the actual choices of speed that road users make. A second reason for adopting an economic perspective, is that this perspective represents a clear normative ideal for individual behaviour, in terms of social efficiency. Normative economic welfare theory proposes social efficiency as an ideal solution to any problem that involves interaction between individuals. A solution is regarded as socially efficient if it is impossible to improve the welfare of one person without reducing the welfare of another person. Such an outcome is often referred to as Pareto-optimal. It is in everybody's interest, since nobody can be made better off without making somebody else worse off.

As far as speed is concerned, a Pareto-optimal solution will be defined as the level of speed which is optimal from a societal perspective. Optimal speed is the speed that minimises the total costs of travel. Any speed that deviates from the optimal level will reduce welfare by increasing costs, irrespective of who pays these additional costs. The main question to be asked is therefore whether a free choice of speed is likely to result in speeds that are optimal from a societal perspective or not. If the answer to this question is negative, regulation of speed choice is necessary in order to bring actual choices closer to the optimal level. More specifically, speed limits are needed if:

1. Driver speed choice gives rise to external effects, i.e. effects that influence the well-being of others, but are not taken into consideration by drivers.
2. Drivers base their choices of speed on an incorrect perception of the impacts of speed, e.g. an underestimation of the effects on accident risk.
3. Drivers have heterogeneous preferences with respect to speed, making the coordination of speed choice between drivers difficult.

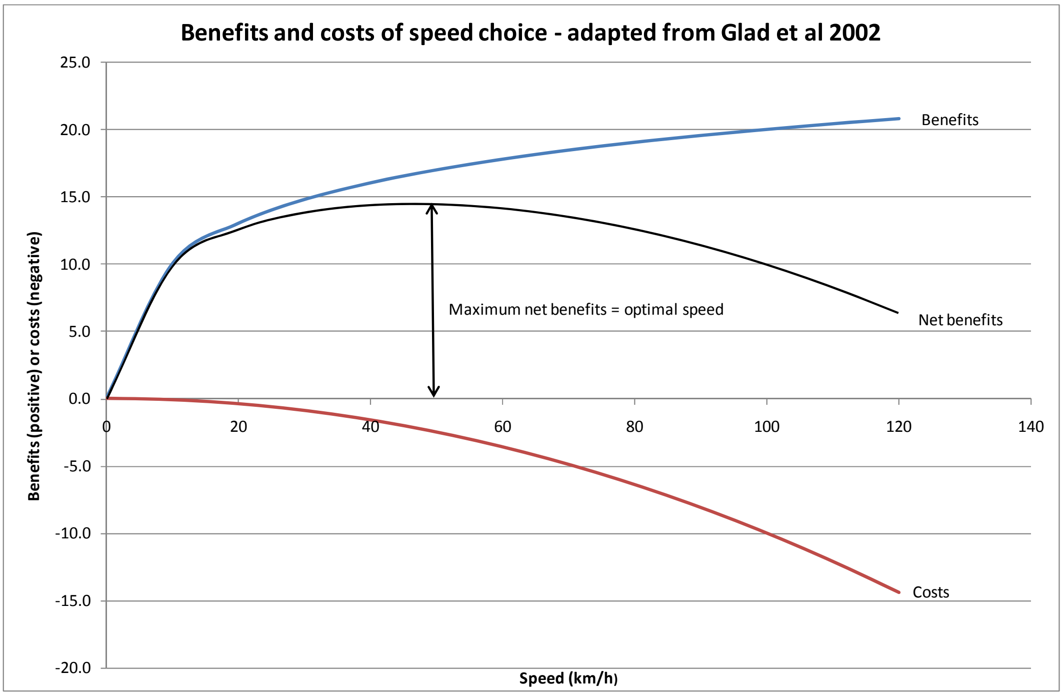
An analysis relying on normative welfare economics requires a formalisation of driver speed choice. These choices and the perceptions underlying them will therefore be modelled formally in terms of continuous functions. An obvious objection to this approach, is that it does not reflect the way speed choice is perceived and experienced by each driver. This criticism is correct, but any formal model should be interpreted in “as if” terms, i.e. driver behaviour can be modelled as if it obeyed the functions proposed here. A model which is much closer to what driver mentally experience has been proposed by Vaa (2003, 2007). His model is intended as an explanatory model, and has a different analytical purpose from the models employed here.

6.2 The concept of rationality as applied to speed choice

Speed is a continuous variable. The choice of speed can therefore be modelled as an optimisation problem akin to consumer choice of the bundle of commodities that maximises preference satisfaction. Glad et al. (2002) present a model of speed choice as an optimisation problem. Figure 5 shows the model. Speed is shown on the horizontal axis, benefits (positive numbers) or costs (negative numbers) on the vertical axis.

The assumption that drivers try to choose their most preferred (i.e. optimal) speed will be made in the analyses that follow. The qualification “try to choose” is used because, as will be discussed below, drivers are not always in the position to choose their most preferred speed, but choose to adapt to the speed of traffic, rather than maintaining a speed that deviates greatly from the mean speed of traffic.

Furthermore, it will be assumed that drivers base the choice of speed on their perceptions of the costs and benefits of different speeds. These perceptions need not be correct. On the contrary, one of the main points made in the analyses presented in this chapter is that to the extent that driver speed choice is based on incorrect perceptions of the impacts of speed, the choices are not necessarily optimal from a societal point of view even they are optimal from the driver’s point of view.



Source: TØI-report 1034/2009

Figure 5: Speed choice as an optimisation problem

Modern theory of rational choice defines rationality in terms of the beliefs and preferences of the individual. It is, as Jon Elster states (2007, page 209) "subjective through and through", i.e. it refers only to what individuals believe and prefer and not to some external standard. Elster adds that: "One might, to be sure, take the word "rational" in an objective sense, implying that a rational agent is one who makes decisions that make his life go better as judged by objective criteria such as health, longevity, or income. Used in this way, however, the idea would not have any explanatory power." This point of view is obviously correct as far as explaining choices by showing that they were (subjectively) rational is concerned. But this does not mean that any subjectively rational choice carries any normative status as far as guiding public policy is concerned.

Herbert Simon (1976, page 76) makes the following distinction between subjective and objective rationality: "A decision may be called "objectively" rational if in fact it is the correct behaviour for maximizing given values in a given situation. It is "subjectively" rational if it maximizes attainment relative to the actual knowledge of the subject."

The distinction made by Simon is used as the starting point for the analysis. It is an objective fact that speed choice has impacts on travel time, fuel consumption, accident risk, accident severity, traffic noise, air pollution and road wear. If a driver fails to consider all these impacts and assign due weight to them in choosing speed, speed choice is not objectively rational and may generate external effects that would have been less severe if all impacts had been fully considered. It is an objective fact that the risk of an injury accident increases by about the second power of speed. If a driver thinks otherwise, speed choice is based on an incorrect belief and is therefore not objectively rational. If a driver believes that he can stop before hitting an obstacle, when in fact the minimum conceivable reaction time, road surface friction and the braking power of the car makes this physically impossible, the driver is wrong and is not acting in an objectively rational manner. In short: if driver speed choice is not objectively rational, it will not produce outcomes that are socially desirable.

6.3 The first condition: impacts that are considered

Several studies have examined factors that influence speed choice (Nilsson 1991; Rajalin and Summala 1996; Åberg, Larsen, Glad and Beilinson 1997; Haglund and Åberg 2000; Letirand and Delhomme 2005; Stradling 2007; Wallén Warner and Åberg 2008; Schmid Mast et al. 2008; Tarko 2009). Of particular interest are studies that identified multiple impacts of speed and tried to determine the importance of these impacts for driver speed choice.

Nilsson (1991) asked a sample of drivers why they were not driving faster. A total of twelve reasons were given and drivers rated the importance of these reasons. Among drivers who complied with the speed limit, acceptance of the speed limit was the most important reason for not driving faster. Increase in emission was rated at place eight (out of twelve) and increased noise was rated at place eleven. Among drivers who exceeded the speed limit by less than 10 km/h, increase of emissions was rated at place eight and increased noise at place eleven out of the twelve reasons stated. Among drivers who exceeded the speed limit by more than 10 km/h, increase of emissions and noise were the two least important reasons they gave for not driving faster. In other words, consideration of impacts on noise and emissions does not prevent a driver from driving fast and are, even among those who comply with speed limits, rated as the least important factors influencing speed choice. Nilsson also asked drivers why they were not driving slower. The most important reason given was that driving slower would impede traffic. Among the fastest drivers, dullness was also given as an important reason for not driving slower.

Rajalin and Summala (1996) obtained slightly different results. They asked a sample of slow drivers why they were driving slowly. Fifteen reasons were listed. The most important reason given for driving slowly was that the driver had plenty of time. Consideration for car, fuel and environment was rated at sixth place among the fifteen reasons, suggesting that it does carry some weight among slow drivers. It was, however, clearly not the most important reason for driving slowly.

Stradling (2007) found that large majorities of drivers stated that they would drive slower in fog, in heavy rain, in darkness or on unfamiliar roads. Interestingly, 69 % of drivers also stated that they would drive slower if traffic was slower than their normal speed. 55 % stated that they would speed up if late for a meeting or an appointment; 30 % stated that they would speed up if traffic was faster than their normal speed. Impacts of speed choice on noise or pollution were not considered in this study.

Wallén Warner and Åberg (2008) found that drivers regarded it as likely that exceeding speed limits in urban areas would increase pollution and rated this impact as very bad. This knowledge and evaluation did not, however, correlate very strongly with driver intention to exceed speed limits. Among ten factors, it was rated at place seven in terms of the strength of the correlation with the intention to exceed speed limits in urban areas. With respect to the intention to exceed speed limits in rural areas, it was once more found that drivers believed that this would increase pollution and regarded this impact as very undesirable. This belief and evaluation had only minor influence on their intention to speed. The correlation between the assessment of impacts on pollution and intention to speed was only a non-significant .07, the eleventh weakest correlation of fourteen factors that were included.

The study of Stradling (2007) found that driver speed choice was influenced by the speed of traffic: a large proportion of drivers stated that they would adapt to the speed of traffic even if it differed from their own most preferred speed. Results along the same lines were found by Åberg et al. (1997) and Haglund and Åberg (2000). The latter study, in particular, found evidence of what has been termed "false consensus": Drivers who drove faster than the average erroneously believed that other drivers also did so.

Taken together, these studies suggest that while drivers know that speed influences noise and pollution, and regard an increase in noise and pollution as undesirable, consideration of these impacts carry little weight in determining the choice of speed. It is reasonable to assume that impacts of speed choice on noise and pollution are to a large extent external from the driver's point of view.

Neglecting impacts on noise and pollution may have significant implications for speed choice. In an analysis of optimal speed limits, Elvik (2002) found that impacts on noise and pollution represent about 16 percent of the total societal costs of travel at a speed of 50 km/h in urban areas and about 4 percent of the total societal costs of travel at a speed of 80 km/h in rural areas. Official Norwegian monetary valuations of travel time, accidents, noise and air pollution were applied (Eriksen et al. 1999). In urban areas, the costs of noise and air pollution reach their minimum at a speed of 40 km/h.

6.4 The second condition: assessing the impacts correctly

The fact that drivers do not include all societal impacts of speed when choosing their speed implies that there will be external effects of these choices. But do drivers correctly assess the impacts they do include when choosing speed? These impacts include at least travel time and the risk of accidents, possibly also vehicle operating costs. The question is whether drivers correctly assess the impacts of speed choice on travel time and accident risk.

6.4.1 Speed and travel time

The relationship between mean speed and travel time for a given distance is very simple. It is given by:

$$\text{Travel time} = \frac{\text{Distance in km}}{\text{Mean speed in km per hour}}$$

One would believe that the simplicity of this relationship would make it easy to estimate the change in speed required to save a certain amount of time. Svenson (2008, 2009) conducted a series of experiments that show that people do not assess correctly the change in speed required to save a certain amount of travel time. Svenson gave a sample of students at the Royal Institute of Technology in

Stockholm a series of tasks that were all framed as follows: “If you are to drive 100 km, increasing your speed from 30 to 40 km/h will save you 50 minutes of travel time. Suppose your speed is 60 km/h. What speed would you then have to adopt in order to save 50 minutes?” The correct answer is 120 km/h. If you drive 100 km at 60 km/h, the trip will take 1 hour and 40 minutes; at 120 km/h it will take 50 minutes, resulting in a saving of 50 minutes. Surprisingly, students were not able to correctly estimate the changes in speed required to save a certain amount of travel time. Table 14 gives a sample of the results.

In general, when the speed stated in the reference situation was low, and students were asked to estimate the required increase from a high baseline speed, they underestimated how much speed needed to be increased. Conversely, when the speed stated in the reference situation was high, and students were asked to estimate the required increase from a low baseline speed, they overestimated how much speed needed to be increased. In other words, the saving in travel time by small increases of a high speed is overestimated, while the saving in travel time by a small increase in a low speed is underestimated. The relationship between speed and travel time is thus perceived to be more linear than it actually is. Similar results were reproduced in a study by Fuller et al. (2009).

Table 14: Sample of results from study of Svenson (2008, 2009)

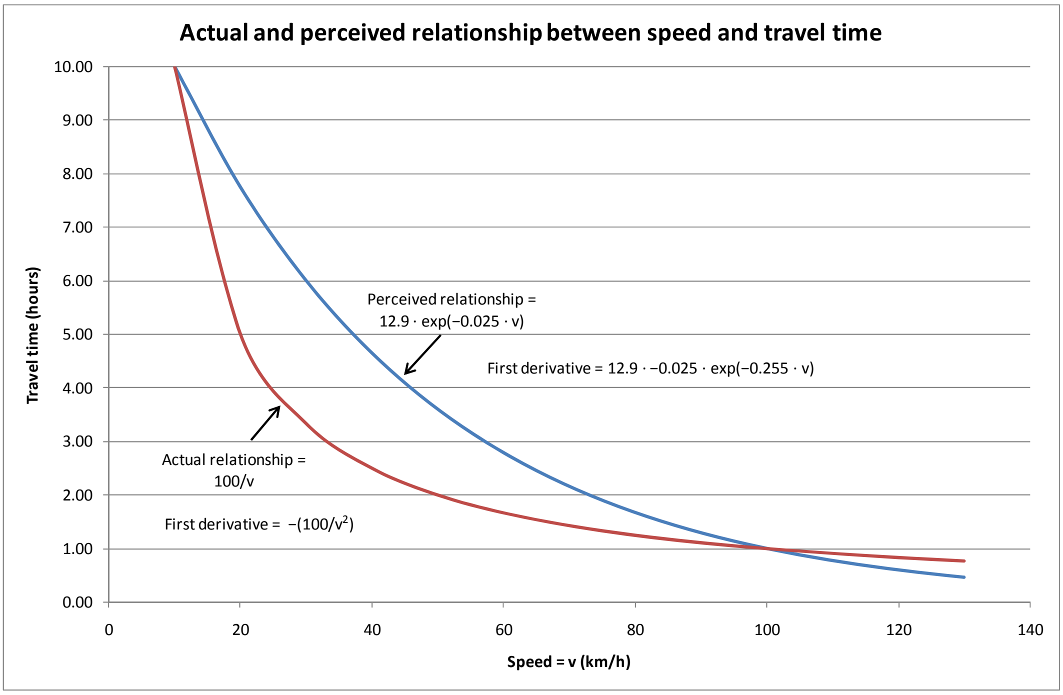
Reference situation (A)		**Situation where new speed is to be stated (B)**		
Initial speed	**New speed**	**Initial speed**	**Stated new speed**	**Correct new speed**
30 km/h	40 km/h	60 km/h	73 km/h	120 km/h
40 km/h	50 km/h	80 km/h	95 km/h	130 km/h
60 km/h	120 km/h	40 km/h	75 km/h	60 km/h
60 km/h	120 km/h	30 km/h	66 km/h	40 km/h
30 km/h	50 km/h	60 km/h	88 km/h	300 km/h
60 km/h	130 km/h	30 km/h	77 km/h	40 km/h

Source: TØI-report 1034/2009

Figure 6 shows the actual and perceived relationship between speed and travel time. The actual relationship is described by the function: 100/v, in which v is speed in kilometres per hour. The perceived relationship has been described in terms of the function:

$$\text{Perceived relationship between speed and travel time} = 12.9 \cdot \boldsymbol{e}^{(-0.025 \cdot \boldsymbol{v})} \qquad (5)$$

The perceived relationship has a flatter slope than the true relationship for speeds below about 30 km/h. For higher speeds, the slope of the perceived relationship is steeper than for the true relationship. The function for the perceived relationship between speed and travel time is consistent with the findings of Svenson and Fuller et al., but is a smoothing of their findings to permit a more formal analysis.



Source: TØI-report 1034/2009

Figure 6: Actual and perceived relationship between speed and travel time

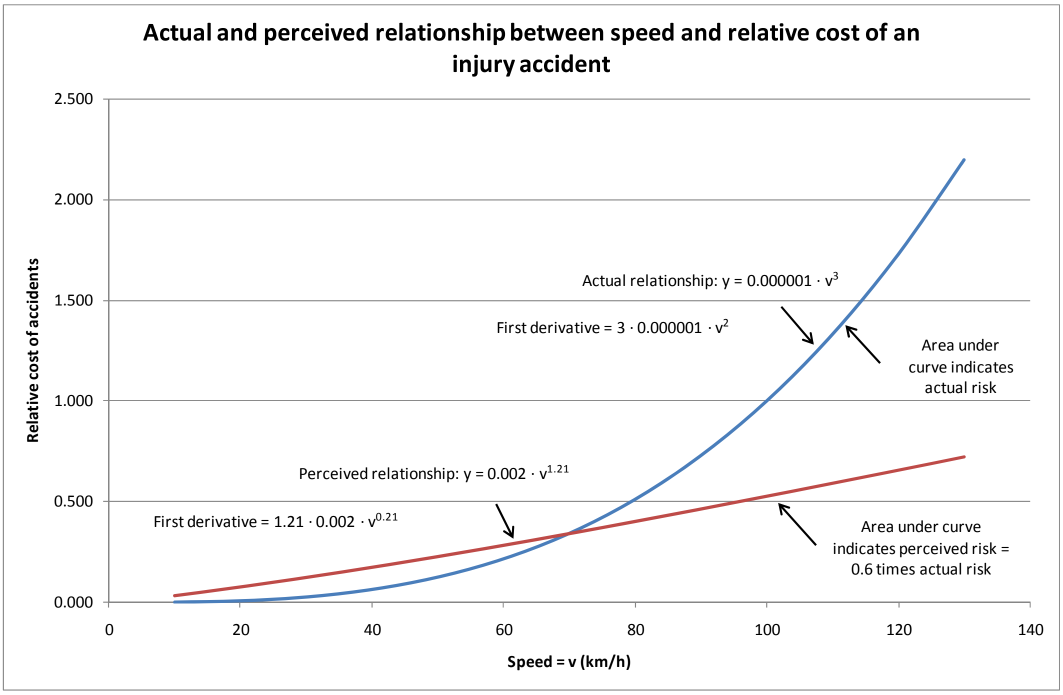
The erroneous perception of the relationship between speed and travel time implies that gains in travel time of a given increase in speed from a low initial speed are underestimated, meaning that drivers believe they must increase speed more than they actually have to in order to save a certain amount of time. Conversely, gains in travel time by increasing a comparatively high speed are overestimated.

6.4.2 Speed and accident risk

Svenson (2008, 2009) also asked students to state the increase in the risk of an injury accident associated with specific increases in speed. According to the Power Model of the relationship between speed and road accidents (Elvik, Christensen and Amundsen 2004), the risk of an injury accident increases in proportion to the second power of the relative change in speed:

$$\frac{\text{Number of accidents after}}{\text{Number of accidents before}} = \left(\frac{\text{Mean speed of traffic after}}{\text{Mean speed of traffic before}}\right)^2$$

Students, however, think that the increase in the risk of an injury accident is much smaller. Figure 7 shows the relationship between increases in speed and increases in the cost of accidents according to the students and according to the Power Model. The reference here is to the Power Model as published in 2004, since the update presented in this report had not been published when Svenson reported his study.



Source: TØI-report 1034/2009

Figure 7: Actual and perceived relationship between speed and the cost of an accident

It was even more remarkable that students did not think that the risk of a fatal accident increased more than the risk of an injury accident. The Power Model, which is firmly supported by empirical research, suggests that the risk of a fatal accident increases by about the fourth power of the relative change in speed. Thus, students grossly underestimate both the risk of an accident and accident severity. Svenson asked a sample of traffic engineering students the same questions, but these students were not more well-informed than the sample of psychology students that Svenson mainly relied on.

Speed influences both the risk of becoming involved in an accident and the severity of injuries. Both effects can be captured in a single function by means of the Power Model by using exponents that apply to the number of fatalities, the number of seriously injured road users and the number of slightly injured road users. The actual relationship between the changes in speed and the number of killed or injured road users was estimated by means of the following function, using a speed of 100 km/h as reference:

$$\text{Actual effects of changes in speed} = \left(\frac{v_i}{100}\right)^{4.5} + \left(\frac{v_i}{100}\right)^{3.0} + \left(\frac{v_i}{100}\right)^{1.5} \qquad (6)$$

100 is the reference speed (km/h); v_i is any other speed (varying between 10 km/h and 130 km/h); 4.5 is the exponent for fatalities; 3.0 is the exponent for seriously injured road users; 1.5 is the exponent for slightly injured road users. Equation 2 gives relative changes in the number of fatalities, seriously injured road users and slightly injured road users as a result of relative changes in speed. To summarise these changes in terms of a single function, the relative changes were converted to

accident costs by applying official monetary valuations for Norway (Statens vegvesen 2006) and assuming that, as an average for all public roads, 2.25 % of injuries are fatal, 8.40 % are serious and 89.35 % are slight (based on official accident statistics for Norway 2000-2008). The official valuations as of 2005 were 26.5 million NOK for a fatality (1 NOK = 0.11 Euro as of July 2009), 7.8 million NOK for a serious injury and 0.8 million NOK for a slight injury. The resulting function, calibrated to equal 1.00 at a speed of 100 km/h was:

$$\text{Actual accident costs as a function of speed} = 0.000001 \cdot v^3 \qquad (7)$$

The perceived relationship between speed and the expected costs of accidents was estimated as:

$$\text{Perceived accident costs as a function of speed} = 0.002 \cdot v^{1.21} \qquad (8)$$

The constant term was set so that the area under the curve representing the perceived relationship between speed and relative accident cost was equal to 0.6 times the area under the curve representing the actual relationship between speed and relative accident costs. This is based on a study by Andersson (2007), showing that the median perceived risk of being killed in a road accident is about 60 % of the actual risk of being killed (i.e. people underestimate the risk). Figure 7 shows the two functions.

6.4.3 Impact speed – the illusion of control

The third type of task Svenson (2008, 2009) gave students was as follows: "A driver who drives at 25 km/h will just be able to stop before hitting an obstacle that suddenly appears on the road. Your speed is 40 km/h. At what speed do you think you will strike the obstacle?" The most likely actual impact speed was estimated by assuming a reaction time of 1 second (which is short for a surprising situation; Shinar 2007) and a retardation of 0.8 g. Actual impact speed was compared to the impact speed estimated by students. Table 15 gives a sample of results.

Table 15: Perceived and actual impact speed in given accident scenarios

Initial speed for cars that stops (km/h)	Your speed (km/h)	Subjectively stated impact speed (km/h)	Actual impact speed (km/h)
25	40	20.17	40.00
80	90	38.60	44.46
60	130	71.77	130.00
50	70	33.43	57.89
80	120	59.33	99.86
25	50	21.33	50.00
110	130	58.10	74.38
70	110	57.83	95.96

Source: TØI-report 1034/2009

As can be seen, students underestimated impact speed considerably. If a similar underestimate is prevalent in actual driving, drivers will adopt too small safety margins. Driving speeds in darkness are, in general, too high to enable drivers to stop and perform evasive manoeuvres to avoid an accident when only dipped headlights are used and an obstacle suddenly appears (Shinar 2007).

6.5 The third condition: coordinating speed choice

The speed of traffic is the result of the coordination among drivers of their individual speed choices. This coordination would be easy if all drivers prefer to drive at the same speed. Evidence suggests, however, that this is not the case. There is considerable variation between drivers with respect to preferred speed.

Goldenbeld and van Schagen (2007) assessed the credibility of speed limits by asking a sample of drivers to state: (1) what they regarded as an appropriate speed limit for a sample of 27 road sections, and (2) what they regarded as a safe speed when driving on each of the road sections. All road sections had a speed limit of 80 km/h, but drivers were not informed about this. Safe speed, as stated by drivers, varied between 71 and 92 km/h. The study shows that different groups of drivers differ with respect to their views regarding safe speed. In order to explore how preferences regarding safe speed were distributed in the sample of drivers, Goldenbeld and Van Schagen were asked to provide the data for the study, which they kindly did. Figure 8 is based on driver answers to the question regarding safe speed.

As can be seen, there are two distinct groups among drivers. One large group regarded 80 km/h as a safe speed. Another large group regarded 100 km/h as a safe speed. Preferences regarding safe speed are clearly bimodal, suggesting that the coordination between the two main groups of drivers will be difficult: if traffic speed is 80 km/h, many drivers will feel that this is too slow; if traffic speed is 100 km/h, many drivers will feel that this is too fast.

Based on the distribution of preferences shown in Figure 8, speed choice can be modelled as a coordination game between two groups of drivers: the fast movers and the slow movers. Table 16 shows this game. The ordinal preferences of drivers are indicated by numbers; 4 is the most preferred outcome, 1 is the least preferred outcome. The fast movers choose between columns; their payoffs are shown in the upper right corner of each cell of the Table. The slow movers choose between rows; their payoffs are shown in the bottom left corner of each cell of the table. Both groups of drivers are assumed to prefer driving at the same speed as the other group to driving at a speed that differs from the other group.

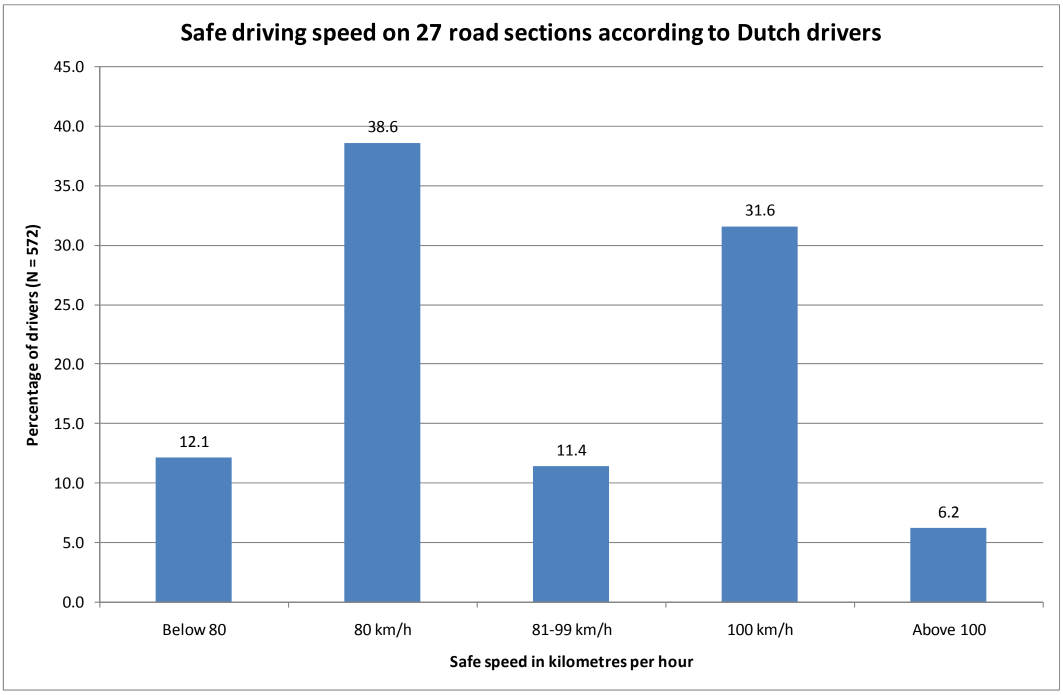


Figure 8: Driver preferences regarding safe speed on roads with a speed limit of 80 km/h. Based on Goldenbeld and van Schagen 2007

For the fast movers, the best outcome is that everybody drives at a 100 km/h. The slow movers will prefer this outcome to driving at 80 km/h, given that the fast movers continue to drive at 100 km/h. However, the most preferred outcome for the slow movers is that everybody drives at 80 km/h. Both this outcome, and the outcome in which everybody drives at 100 km/h, are Nash equilibria, in the sense that no group can get a more preferred outcome by unilaterally changing its choice. The two solutions are also Pareto-optimal, since going from one solution to the other will reduce the payoff for one group while increasing it for the other group. From a societal point of view, however, the choice between the two solutions is not indifferent. The low speed equilibrium will be associated with less accidents and smaller environmental impacts than the high speed equilibrium.

Table 16: Speed choice as a coordination game

The fast movers

The slow movers	80 km/h	100 km/h
80 km/h	(fast mover) 3 4 (slow mover)	(fast mover) 2 2 (slow mover)
100 km/h	(fast mover) 1 1 (slow mover)	(fast mover) 4 3 (slow mover)

Source: TØI-report 1034/2009

The equilibria are not likely to be stable. Connolly and Åberg (1993) explore a contagion model of speeding, in which speed choice is influenced by other drivers. Depending on how sensitive drivers are to the choices made by other drivers, the mean speed of traffic may be determined by the choices made by even a small minority of drivers. Suppose, for example, that a slow driver maintains a speed of 80 km/h. A fast driver may regard this as too slow, but overtaking is a hassle and it may, on balance, be more pleasant to put up with the slow driver and stay in line. If everybody thinks like that, the speed of traffic will be 80 km/h. A driver who is less sensitive to the speeds chosen by other drivers may decide to overtake the slow driver and may thereby induce other drivers to follow suit. Suddenly, everybody will be overtaking the slow driver and the speed of traffic will increase.

6.6 The calculus of misperceptions

As noted above, it will be assumed that drivers choose an optimal speed, i.e. the speed that minimises the subjective costs of driving. As a (admitted gross) simplification, the choice of speed can be modelled as a trade-off between travel time and travel safety. Although there are other impacts of speed, travel time and safety are two of the most important impacts from a driver's point of view.

Following Tarko (2009), it will be assumed that drivers seek to minimise the total costs of travel. These costs are:

Total costs of travel = Costs of travel time + Costs of accidents

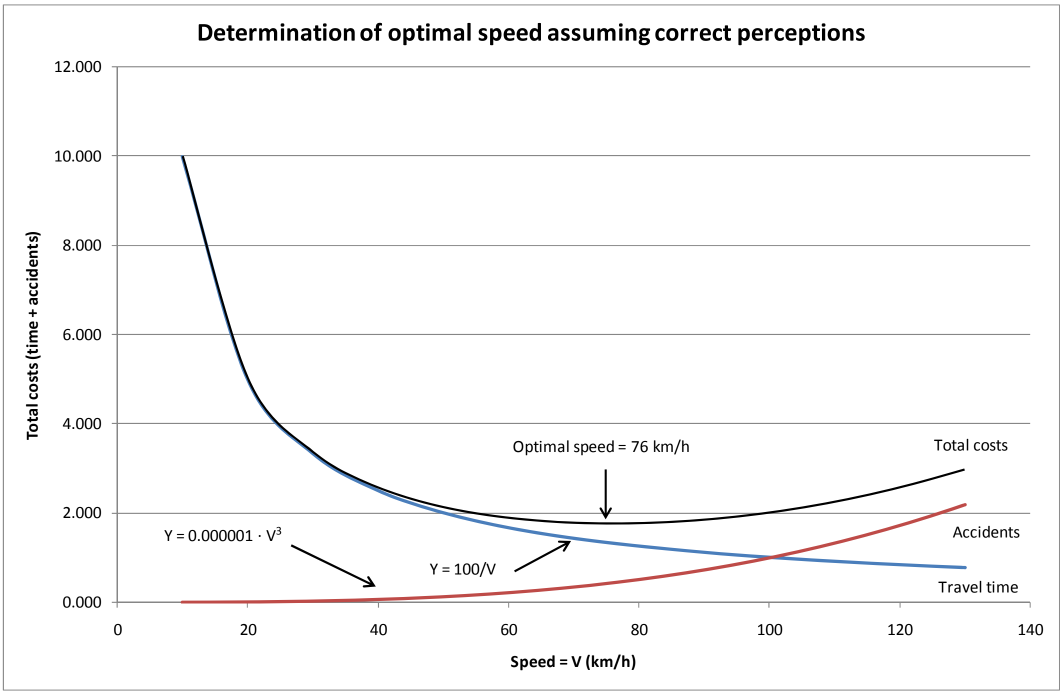
The speed that minimises the sum of the costs of travel time (which, all else equal, are proportional to travel time) and accidents can be found by setting the sum of the first derivatives with respect to travel time and accident costs equal to zero. For the actual relationships, this comes to:

$$\text{Optimal speed (actual relationships)} = -\frac{100}{v^2} + 3 \cdot 0.000001 \cdot v^2 = 0 \qquad (9)$$

Optimal speed is estimated as 76 km/h, as shown in Figure 9. If, on the other hand, the perceived relationships, as modelled above, are used, optimal speed becomes:

$$\text{Optimal speed (perceived relationships)} = [12.9 \cdot -0.0255 \cdot exp^{(-0.0255 \cdot v)}] + [1.2 \cdot 0.002 \cdot v^{0.2}] = 0 \qquad (10)$$

Optimal speed is estimated to be above 130 km/h. This result lacks credibility and is clearly a product of the way the perceived relationships between speed and travel time and speed and relative accident cost have been parameterised. It can be argued that the misperception of the relationship between speed and accident risk is more severe than the misperception of the relationship between speed and travel time. The latter misperception can be corrected by providing drivers with feedback on mean speed and travel time when driving. Speed and travel time can be measured objectively. It is a lot more difficult to measure the level of accident risk in a direct way and give drivers credible feedback to inform them of the impacts of their choice of speed. The fact that the perceived relationship between speed and safety is considerably flatter than the actual relationship implies that the costs of increased speed will almost always be underestimated, in particular at high speeds.



Source: TØI-report 1034/2009

Figure 9: Determination of optimal speed based on actual relationships between speed and travel time and speed and accident cost

6.7 Self-interested preferences for speed limits

Driver misperceptions of the impacts of speed are likely to induce drivers to adopt a higher speed than the speed that would be optimal if the impacts of speed choice were correctly perceived. The choice of speed is, however, the result not just of the perceptions of the impacts, but also of driver preferences regarding speed and speed limits. A number of studies have been made about driver preferences regarding speed limits. These studies show that majority preferences are: (a) in favour of higher speed limits, and (b) self-regarding. The term self-regarding denotes preferences that are based on self-interest only, with little regard to the interests of other road users. Examples are preferences for high speed among owners of fast cars, those who have high income, those who think they are better than average drivers, etc.

According to a Dutch survey (Rienstra and Rietveld 1996) a majority of respondents stated that exceeding the speed limit on freeways (120 km/h) by 20 km/h was acceptable. Almost 80 % were opposed to reducing the speed limit on freeways to 100 km/h.

In a similar survey in Norway (Phillips and Fyhri 2008), 73 % stated that the speed limit on motorways ought to be at least 110 km/h. The current speed limit is 100 km/h on the best sections of motorways, 90 km/h otherwise.

Perhaps the most revealing study of all, is a Swedish study (Johansson-Stenman and Martinsson 2005). According to this study, 54 % wanted to raise the speed limit on motorways in Sweden, either to 120 km/h (25 %) or 130 km/h (29 %). 41 % wanted to keep the current speed limit of 110 km/h. Only 5 % wanted to reduce the speed limit. Johansson-Stenman and Martinsson investigated factors that influenced speed limit preferences. A large number of factors were included and their effect on speed limit preferences estimated by means of multiple regression.

The mean preferred speed limit for the full sample was 118.55 km/h (current speed limit = 110 km/h). If your car was of the most recent vintage (same model year as the year of the survey); you owned a BMW, Mercedes or Porsche; the car was big; you rated yourself as a better than average driver; you earned 50 % more than average; you were male and less than 57, and your political sympathies were right wing, your preferred speed limit was 130.47 km/h. If, on the other hand, your car was 15 years old; the car was not a BMW, Mercedes or Porsche; the car was small; you did not rate yourself as a better than average driver; you earned 50 % less than the average; you were female and above 57, and you had left-wing political sympathies, your preferred speed limit was 109.65 km/h.

In other words, driver preferences about speed limits are influenced by a host of factors, few of which are relevant for determining the optimal speed limits from a societal point of view.

6.8 Discussion

Based on the research reviewed above, it seems clear that driver speed choice is not objectively rational. It is not even subjectively rational in all cases, since interaction with other drivers may prevent a driver from choosing his or her most preferred speed, forcing the driver to put up with driving at a speed that does not maximise his or her utility.

The lack of objective rationality in speed choice is attributable to the following cognitive limitations of driver speed choice:

1. Drivers tend to ignore, or assign minor importance to, impacts of speed that they do not immediately notice or that do not directly affect their personal utility. More specifically, environmental impacts of speed choice are largely ignored by drivers.
2. Drivers do not correctly perceive the relationship between speed and travel time. Gains in travel time attributable to small increases in high speed are overestimated, while corresponding gains attributable to small increases in low speed are underestimated. These misconceptions may lead drivers to commit more serious violations of low speed limits than of high speed limits.
3. Drivers underestimate the increase in the risk of accident associated with increased speed.

4. Drivers underestimate impact speed in situations in which it is clear that an accident is unavoidable, but its severity can be reduced by braking.
5. Driver preferences with regard to safe speed are very heterogeneous, making the coordination of speed choices difficult.

Ignoring environmental impacts of speed may impose significant external impacts in urban areas in terms of noise and air pollution. While these impacts cannot be entirely avoided, they can be minimised by setting speed limits at the speed that minimises the costs of noise and air pollution. In general, these speed limits are lower than the current mean speed of traffic in both urban and rural areas.

Low speed limits have been introduced in residential areas and other areas where there is a high risk of accidents, both in order to reduce risk and to permit residents to stay outdoors and allow children to play without having to worry about traffic all the time. It should therefore be regarded as a serious problem that drivers tend to believe that speed must be increased substantially to save time when initial speed is low.

The fact that the risk of accidents, and injury severity, increases as speed increases has traditionally been an important argument for introducing speed limits. It is, however, by itself not a convincing argument. If it is correct to assume that drivers choose the speed that is optimal, “all things” considered, the resulting number of accidents or injuries should also be regarded as optimal. This assumption is, however, not correct. Drivers tend to ignore some impacts of speed and they do not correctly estimate the impacts of speed choice on safety. Misperception of the impacts of speed is reinforced by the fact that part of the cost of accidents is external from the driver’s point of view (Elvik 1994). The net result is that an “optimism bias” among drivers leads them to choose speeds that are higher than optimal from a societal point of view.

Thus, the lack of rationality characterising driver speed choice would appear to be a strong argument for introducing speed limits. Any speed limits will, however, be a compromise between multiple objectives that are partly conflicting. While safety is best served by low speed limits, reducing travel time is best served by high speed limits. On top of this, driver opinions with respect to speed limits are very heterogeneous. Thus, any speed limit is likely to be unpopular and regarded as either too high or too low by a considerable proportion of drivers.

6.9 Conclusions

Speed is regulated by means of speed limits in all highly motorised countries. Speed limits would not be needed if drivers were able to choose speeds that are optimal from a societal point of view without the guidance given by speed limits. Thus, the rationality of driver speed choice is an important criterion for assessing whether speed limits are justified in terms of normative welfare economics or not. Speed limits would not be justified if driver speed choice was perfectly rational and resulted in outcomes that are optimal from a societal point of view. This chapter has reviewed research that has evaluated various aspects of the rationality of driver speed choice. A fairly strong case can be made that driver speed choice is not objectively rational and that the unaided coordination of speeds among drivers is difficult, because preferences regarding optimal speeds differ greatly.

Moreover, these preferences are shaped by a host of factors that are completely irrelevant when determining speed limits that are optimal from a societal point of view. The lack of rationality in driver speed choice is a strong argument for the need for guiding and constraining this choice by means of speed limits.

7 Discussion and conclusions

7.1 Discussion

There are always two main interpretations of the results of research: methodological and substantive. A methodological interpretation would normally argue that the results of a study cannot be trusted, but are attributable to weaknesses in data and methods. A substantive interpretation would normally argue that the results of a study reflect causal relationships and should therefore be taken seriously.

Both these interpretations were discussed at length in the original report (Elvik, Christensen and Amundsen 2004). It was concluded that the findings most probably reflect causal relationships and are unlikely to be strongly influenced by weaknesses in data or methods. As noted in chapter 2, the new studies that have been added in this update are of better quality than the studies that were originally included. It therefore remains unlikely that the main results of the study can be dismissed on methodological grounds.

Nevertheless, the original study did leave some loose ends. More specifically:

1. The study did not assess the relationship between speed and road safety for specific types of accident; it only dealt with the total number of accidents.
2. The study did not systematically test whether other models of the relationship between speed and road safety fitted the data better than the Power Model.
3. The effects of moderator variables, like type of traffic environment and vehicle age, were not studied in detail.

One of the objectives of this update was to follow up on these loose ends. Another objective was to test whether the effects of speed remain stable as new studies are added to the database.

7.1.1 Impact speed and risk of fatal injury for pedestrian and vehicle accidents

With respect to the first of these points, recently published studies (U.S. Department of Transportation 2005; Rosén and Sander 2009) shed new light on the relationship between impact speed and the probability of sustaining a fatal injury. Both these studies indicate that a logistic function is the best model of the relationship between impact speed and the probability of sustaining a fatal injury.

The study reported by the U. S. Department of Transportation, National Highway Traffic Safety Administration (2005) summarised the relationship between impact speed and the probability of sustaining an injury of a specific level of severity (in terms of the Abbreviated Injury Scale (AIS)) by means of a set of logistic functions. The best fitting function for fatal injury was:

$$\text{Probability of fatal injury (percent)} = 100 \cdot \frac{\boldsymbol{e}^{0.1524 \cdot \boldsymbol{i} - 8.2629}}{1 + \boldsymbol{e}^{1.1524 \cdot \boldsymbol{i} - 8.2629}} \qquad (11)$$

In equation 11, e denotes the exponential function and i denotes impact speed (in miles per hour). Accident data referred to all accidents involving passenger vehicles, in which at least one of the vehicles used the brakes before the accident.

Rosén and Sander (2009) found the following relationship between impact speed and the probability of a pedestrian fatality:

$$\text{Probability of a fatal injury (percent)} = \frac{1}{1 + \boldsymbol{e}^{(6.9 - 0.090 \cdot \boldsymbol{V})}} \qquad (12)$$

In equation 12, e is the exponential function and v is impact speed. Figure 10 shows these functions.

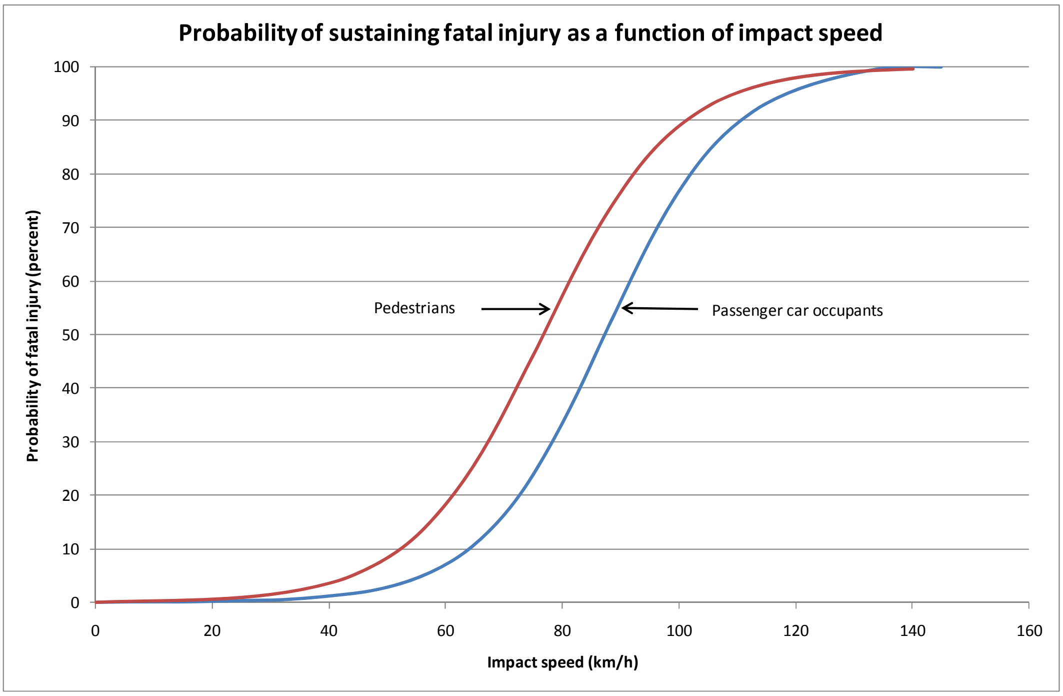


Figure 10: Probability of sustaining a fatal injury as a function of impact speed. Derived from U.S. Department of Transportation (2005) and Rosén and Sander (2009)

The curves are surprisingly close. In particular, the curve for pedestrians shows a considerably higher probability of survival than other studies have indicated (e.g. Anderson et al. 1997). Previous studies have suggested that the risk of a pedestrian fatality is around 80-90 % when impact speed is about 60 km/h. The study by Rosén and Sander (2009) estimated the risk of a pedestrian fatality at an impact speed of 60 km/h to about 20 %. Davis (2001) also estimated the risk of a pedestrian fatality to about 20 % at an impact speed of 60 km/h.

In general, curves will be shifted to the right the larger the vehicle is and the better it protects occupants from injury when an accident occurs.

7.1.2 Alternative models of the relationship between speed and road safety

The curves shown in figure 10, relating the probability of fatal injury to impact speed are both logistic. This functional form is a reasonable model of how the probability of sustaining an injury of a specific severity depends on impact speed. At very low speeds, any impact will be within the limits of biomechanical tolerance; at very high speeds, any impact will expose the body to biomechanical forces that cannot be survived.

Impact speed is, however, very different from the speed of traffic. In most accidents, road users are able to brake or initiate evasive manoeuvres before impact. Mean impact speeds are therefore substantially lower than the mean speed of traffic. While a logistic function is probably the best model of the relationship between impact speed and injury severity, it is not necessarily the best model of the relationship between the mean speed of traffic and the probability of accident occurrence.

The re-analyses of Hauer and Bonneson both suggested that the effects on accidents of changes in speed depend on initial speed. However, the findings of the re-analyses are inconsistent. The inconsistency is shown in Table 17, which also shows the results of analyses based on the consolidated data base, presented in Figure 2 in chapter 5.

Table 17: Estimated percentage change in the number of fatal accidents as a function of initial speed. Results from Hauer, Bonneson and this report

	Estimated percentage change in number of fatal accidents when speed is reduced by 10 percent from initial speed		
Initial speed (km/h)	**Hauer (#)**	**Bonneson**	**This report**
35	−32 %	−37 %	−13 %
45	−31 %	−42 %	−19 %
55	−30 %	−46 %	−53 %
65	−38 %	−49 %	−14 %
75	−37 %	−51 %	−30 %
85	−35 %	−51 %	−59 %
95	−34 %	−51 %	−38 %
105	−34 %	−49 %	−28 %
115	−33 %	−47 %	−18 %

Source: TØI-report 1034/2009

Estimates for freeways and rural roads were used for initial speeds in the range 65-115 km/h; estimates for urban arterials were used for initial speeds in the range 35-55 km/h

Hauer estimated different functions for urban arterials on the one hand and freeways and rural roads on the other hand. Bonneson made no distinction between urban and rural roads. The estimates in this report are also based on all results, irrespective of the type of traffic environment. In practice, however, most estimates based on initial speeds in the range 35-55 km/h will be based on urban or residential streets, whereas most estimates based on an initial speed of 65 km/h or higher will be based on freeways or rural roads.

No smoothing function has been fitted to the estimates in this report. These estimates are therefore somewhat more irregular than the estimates of Hauer and Bonneson. The inconsistency between the estimates is related to the fact that the model fitted by Hauer predicts that the effect of a given reduction in speed will increase the lower initial speed is. This does not seem plausible and is subject to the same criticism as the Power Model. Thus, all else equal, Hauer would predict a larger reduction of fatalities when speed is reduced from 35 to 25 km/h than when it is reduced from 105 to 75 km/h (both these reductions are by 28.6 %).

Bonneson's model, on the other hand, predicts smaller reductions in fatalities for low initial speeds than for high initial speeds. His model also predicts slightly smaller reductions in fatal accidents at the highest initial speeds than at intermediate initial speeds. Both these findings are consistent with the findings in this report.

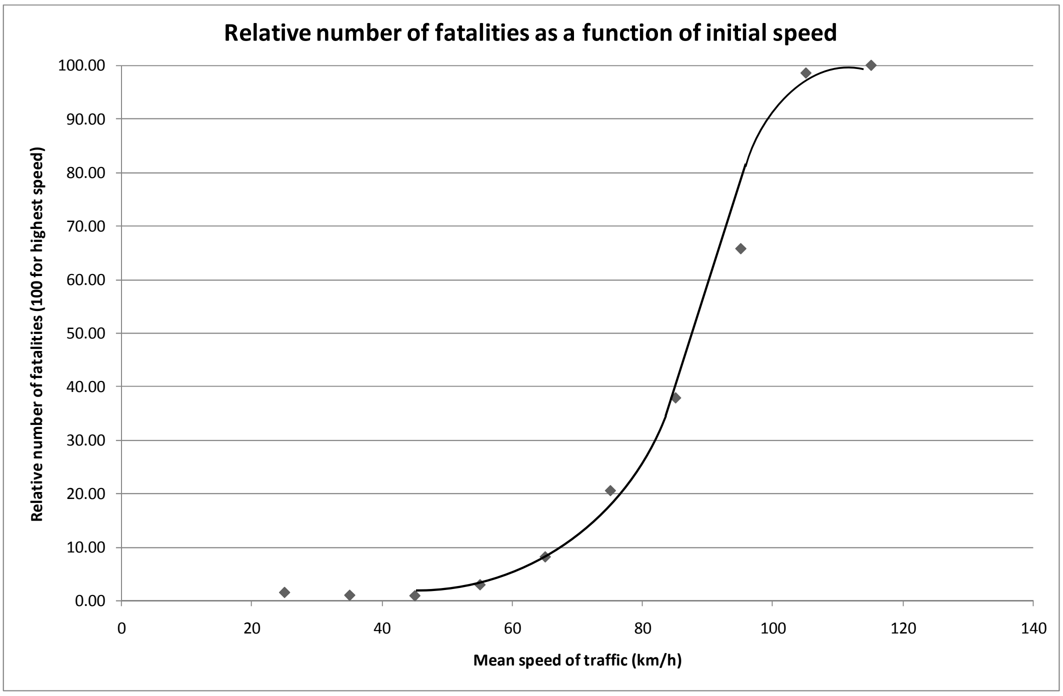
It is not plausible to assume that the effects on fatal accidents of a given reduction in speed increase as initial speed gets lower. When initial speed is low, say, around 30 km/h or less, most impacts will not result in a fatality even if the driver fails to brake before the accident. On the other hand, braking from 80 km/h to 40 km/h can make the difference between a fatal accident and a non-fatal accident.

The findings of Bonneson and this report showing that the effects of changes in very high initial speeds are smaller than the effects of changes in intermediate initial speeds are also somewhat implausible. It seems more plausible to assume that the risk of accident occurrence increases monotonically as speed increases. Surely, one would not expect the risk of accident to reach a plateau at a certain speed and not increase beyond that speed. The Power Model is therefore a plausible model as far as the number of accidents is concerned. It may, however, be less plausible with respect to injury severity. Once the speed of travel is very high, impact speed is also likely to be high with a correspondingly high probability of a fatal injury. The probability of a fatal injury, given an accident, has a ceiling: it cannot exceed the value of 1. The probability of accident occurrence does, however, not have a ceiling in the same sense. It is likely to increase as speed increases, but will never become a certainty. Even trips made at a speed of 200 km/h will not always lead to an accident.

A case can therefore be made for applying two different models to describe the relationship between speed and road safety:

1. One model to describe the relationship between the speed of traffic and the number of accidents of a given severity. The Power Model remains a plausible model of this relationship.
2. One model to describe the relationship between impact speed and the number of accident victims at a given level of injury severity. A logistic model is plausible for this relationship.

Figure 2 in Chapter 5 indicated that the number of fatal accidents increased monotonically as the speed of traffic increased. Although the estimates of the exponent were somewhat lower at higher speeds that at intermediate speeds, there was no clear tendency indicating a turning point or a plateau. Consider, by contrast, Figure 11 below, which shows the relative number of fatalities as a function of the mean speed of traffic.



Source: TØI-report 1034/2009

Figure 11: Relative number of fatalities as a function of the mean speed of traffic

It is seen that the number of fatalities is almost constant at speeds below 45 km/h and above 100 km/h. This is consistent with a logistic model accommodating both a floor effect and a ceiling effect.

7.1.3 Traffic environment as a moderator variable

The re-analyses of Hauer and of Cameron and Elvik indicate that traffic environment is a moderator variable for the effects of speed on accidents and injuries. The analyses in this report confirm the findings of these re-analyses. The exponents of the Power Model are lower in urban areas than in rural areas and on freeways. This finding is very consistent. One may therefore obtain more precise estimates of the effects of changes in speed by applying different exponents for urban and rural areas in the Power Model.

It may perhaps seem counterintuitive that the effects of changes in speed are smaller in urban areas than in rural areas and on freeways (motorways). On closer reflection, however, the finding is reasonable. Urban areas are characterised by a more complex traffic environment than rural areas. There are more junctions, denser traffic, and more mixed traffic. Pedestrians and cyclists are usually more numerous than in rural areas, and in particular on freeways, where pedestrians and cyclists are not allowed to travel. Traffic control is usually more advanced in urban areas than in rural areas, featuring elements such as roundabouts, traffic signals, one-way streets, environmental streets and pedestrian crossings. Some of these traffic control devices are intended to keep speed low.

In general, therefore, safety in urban areas is influenced by a large number of risk factors interacting with each other. A study which clearly illustrates this is the study of urban safety by Greibe (2003). He estimated the effects of several variables on the number of accidents on urban roads. Figure 12 gives a summary of the main findings.

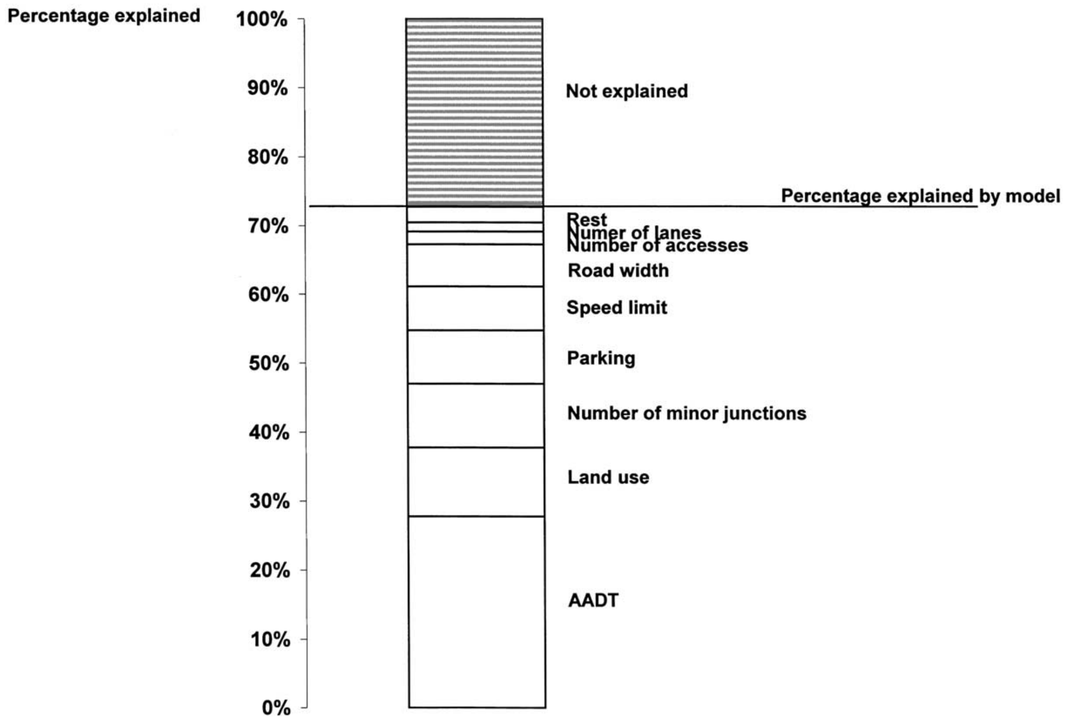


Figure 12: Contribution by various factors to explaining systematic variation in accident counts on urban roads. Based on Greibe 2003

As can be seen, many factors contributed to explaining systematic variation in the number of accidents; speed limit, which is closely related to the mean speed of traffic, contributed less than a number of other factors. This pattern is typical of complex traffic environments. A multitude of risk factors contribute to accidents, but no single factor makes a dominant contribution.

On freeways, the situation is very different. Many of the risk factors that contribute to accidents on urban roads or lower standard rural roads have been eliminated. There are no pedestrians or cyclists. Slow moving motor vehicles are not allowed. Road alignment is gentle with no surprising curves. Sight distances are always longer than stopping distances at legal speeds. There are no at-grade junctions. There are no access points to abutting properties. The road is wide and the road surface is kept in good condition. A median separates traffic in opposite directions. Roadside hazards are always protected by guard rails. In short: the road has been built as safe as it can be. One of the few risk factors that remains is speed.

It is not correct that speed does not matter on freeways, because these roads have been built according to the highest design standards. On the contrary, speed is an important risk factor because so many other risk factors have been eliminated.

7.2 Conclusions

7.2.1 The frame of reference

There are a number of choices to be made when deciding what to conclude from the present study. More specifically, conclusions should ideally be:

1. Based on the methodologically best studies
2. Based on the most recent studies
3. Based on the best-fitting model of the relationship between changes in speed and changes in road safety
4. Structured so as to capture the effects of important moderator variables
5. Framed so as to satisfy minimal requirements of logical consistency.

Unfortunately, it is not easy to formulate the conclusions of the study in a way that fully satisfies all these requirements.

The results of studies that differ with respect to control for potentially confounding factors have been compared in Table 12 in Chapter 5. The results of studies published in different decades have been compared in Figure 1. For both fatal accidents and injury accidents, the mean estimates of power agree well for the best-controlled studies and the most recent studies. For property-damage-only accidents, the best-controlled studies suggest a lower exponent than the most recent studies. For fatalities, the best-controlled studies suggest a higher exponent than the most recent studies.

As far as different models of the relationship between changes in speed and changes in the number of accidents or injured road users is concerned, the choice is between the Power Model and a model permitting the effect of changes in speed to depend on initial speed, like an exponential model or a logistic model.

The re-analyses made of the 2004-study all conclude that the effects of changes in speed vary according to initial speed. In the models developed by Hauer and Bonneson, this variation is captured in terms of non-linear models with parameters allowing the effects of a given relative change in speed to vary depending on the level of speed before the change. However, none of these models are entirely plausible. The model developed by Hauer fits the data only marginally better than the Power Model and predicts that the effect on accidents of a given relative change in speed are greater the lower the initial speed. Besides, the model discarded 137 of the original 460 estimates of the relationship between changes in speed and changes in road safety. By contrast, the model developed by Bonneson predicts that the effects, at least on fatal accidents, of changes in speed are greatest at speeds between 50 and 100 km/h and smaller for higher or lower speeds.

The re-analysis of Cameron and Elvik also supports the conclusion that the effects of speed on road safety depend on initial speed. This is evident from the fact that the values of the exponents in the Power Model are lower for urban and residential roads, where the speed of traffic is lower, than for rural roads and freeways.

It is plausible that the effects on accidents of a given relative change in speed are lower at low initial speeds than at high initial speeds. This follows directly from the fact that, ceteris paribus, less kinetic energy is involved in low-speed impacts than in high-speed impacts. The smaller the kinetic energy involved, the less likely it is to exceed human tolerance of biomechanical impacts and the structural integrity of vehicles.

There are two ways of representing the fact that the effects of a given relative change in speed vary depending on initial speed. One way is by means of the more complex models developed by Hauer and Bonneson. The other is by keeping the Power Model, but developing one set of exponents for "low-speed conditions" and another set of exponents for "high-speed conditions". In this report, the latter option has been chosen, mainly on account of parsimony and simplicity. The Power Model is simpler and more parsimonious (i.e. requires fewer parameters to be estimated) than exponential or logistic models. On the other hand, adopting the Power Model involves accepting a more crude approximation to the non-linearity of the effects of speed than a more complex model would allow for.

The issue of whether another model fits the data better than the Power Model is perhaps more salient with respect to injury severity than with respect to the number of accidents. It is unlikely that the relationship between speed and the number of accidents flattens out at high speeds. It seems more likely that the risk of an accident increases monotonically as speed increases, which is consistent with the Power Model. Injury severity, on the other hand, is likely to show a logistic relationship to impact speed. The probability of sustaining an injury of a given severity, or higher, is low at low speeds, then rises sharply and becomes a certainty at high speeds.

However, the relationship between impact speed and injury severity should not be mixed up with the relationship between the mean speed of traffic and the number of accident victims. The Power Model refers both to the number of accidents and the number of accident victims. The only reason why a separate set of exponents has been proposed for accident victims is the fact that, on average, there is more than one victim per accident. Changes in speed may influence not just the number of accidents but also the number of victims per accident. Again, it seems reasonable to assume that the relationship between speed and the number of victims sustaining an injury of a given severity is monotonic.

The exponents applying to the number of accident victims should not be inconsistent with the exponents applying to the number of accidents. A numerical example shows how an inconsistency can arise. Suppose there are 100 fatal accidents in which 115 road users are killed. Speed is reduced by 10 %. Using an exponent of 3.5 for fatal accidents, it can be estimated that the number of fatal accidents will be reduced to about 69. If the exponent for fatalities is 4.8, the number of fatalities will be reduced to 68, which is logically inconsistent, as there cannot be less than 1 fatality per fatal accident.

In general, the number of fatalities per fatal accident is around 1.10-1.15; the number of seriously injured road users per serious injury accident is around 1.20-1.25; the number of slightly injured road users per slight injury accident is around 1.35-1.45, and the number of injured road users per injury accident (all levels of severity) is around 1.40-1.50. As a rule of thumb, to avoid the type of inconsistency shown above, the exponents applying to the number of accident victims should not be greater than the exponents applying to the number of accidents by more than the squared value of the mean number of victims per accident. Thus, if the exponent for fatal accidents is 3.5, the exponent for fatalities should not be greater than: $3.5 \cdot 1.15^2 = 4.6$.

The main elements of the frame of reference serving as the basis for the conclusions drawn in this report can be summarised as follows:

1. The Power Model is adopted as an adequate model of the relationship between changes in speed and changes in road safety.
2. The exponents in the Power Model should be stratified according to: (a) Traffic environment (urban/residential versus rural/freeway); (b) Accident or injury severity; (c) Whether they refer to the number of accidents or the number of accident victims.
3. The exponents will be as close as possible to those estimated in recent high-quality studies.
4. The exponents applying to accident victims should be harmonised with the exponents applying to the number of accidents to avoid inconsistency, i.e. estimates implying that changes in speed can change the number of victims to less than 1 per accident.
5. The exponents applying to all injury accidents and all injured road users should have values that are lower than the exponents for fatal and serious accidents and victims, but higher than the exponents for slight injury accidents and victims.

Summary estimates of the exponents conforming to this frame of reference are given below.

7.2.2 Summary estimates of exponents for the Power Model

Table 18 gives summary estimates of the exponents for the Power Model. With few exceptions, these estimates are close to the summary estimates presented in Tables 8 and 10 in Chapter 4. Confidence intervals are based on the standard errors given in Tables 8 and 10. These standard errors are based on conventional meta-analysis, not meta-regression.

The estimates refer to the stated level of accident or injury severity. Levels of accident- or injury severity are treated as mutually exclusive categories. The summary estimates of the exponents for all injury accidents and all injured road users have been adjusted downward. The estimates emerging from the analysis are too high to satisfy the consistency condition listed in point 5 above.

Table 18: Summary estimates of exponents for the Power Model of the relationship between changes in speed and changes in road safety

	Summary estimates of exponents by traffic environment					
	Rural roads/freeways		Urban/residential roads		All roads	
Accident or injury severity	**Best estimate**	**95 % confidence interval**	**Best estimate**	**95 % confidence interval**	**Best estimate**	**95 % confidence interval**
Fatal accidents	4.1	(2.9, 5.3)	2.6	(0.3, 4.9)	3.5	(2.4, 4.6)
Fatalities	4.6	(4.0, 5.2)	3.0	(-0.5, 6.5)	4.3	(3.7, 4.9)
Serious injury accidents	2.6	(-2.7, 7.9)	1.5	(0.9, 2.1)	2.0	(1.4, 2.6)
Seriously injured road users	3.5	(0.5, 5.5)	2.0	(0.8, 3.2)	3.0	(2.0, 4.0)
Slight injury accidents	1.1	(0.0, 2.2)	1.0	(0.6, 1.4)	1.0	(0.7, 1.3)
Slightly injured road users	1.4	(0.5, 2.3)	1.1	(0.9, 1.3)	1.3	(1.1, 1.5)
Injury accidents – all	1.6	(0.9, 2.3)	1.2	(0.7, 1.7)	1.5	(1.2, 1.8)
Injured road users – all	2.2	(1.8, 2.6)	1.4	(0.4, 2.4) #	2.0	(1.6, 2.4)
PDO- accidents	1.5	(0.1, 2.9)	0.8	(0.1, 1.5)	1.0	(0.5, 1.5)

Source: TØI-report 1034/2009

Confidence interval specified informally

The consistency of the exponents for rural and urban roads to those applying to all roads has been tested by means of Norwegian accident data. The results indicated a high degree of consistency. In Norway, most police reported accidents occur on rural roads.

The uncertainty of the exponents varies a great deal. A couple of the exponents are not statistically significant at the 5 % level, as can be seen from the confidence intervals given in the table. In general, the exponents are somewhat lower than those found in the original study. This is particularly true for injury accidents (all) and injured road users (all).

Despite this, speed remains a very important risk factor. It has a greater effect on the number of accidents and injury severity than almost all other known risk factors.

The case for having speed limits has been re-examined in this report. It is concluded that speed limits are needed because driver speed choice is characterised by a neglect of important impacts of speed, an erroneous perception of the impacts that are included and heterogeneous preferences among drivers regarding safe speeds.

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