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Driving speed and the risk of road crashes: A review

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Abstract

Driving speed is an important factor in road safety. Speed not only affects the severity of a crash, but is also related to the risk of being involved in a crash. This paper discusses the most important empirical studies into speed and crash rate with an emphasis on the more recent studies. The majority of these studies looked at absolute speed, either at individual vehicle level or at road section level. Respectively, they found evidence for an exponential function and a power function between speed and crash rate. Both types of studies found evidence that crash rate increases faster with an increase in speed on minor roads than on major roads. At a more detailed level, lane width, junction density, and traffic flow were found to interact with the speed–crash rate relation. Other studies looked at speed dispersion and found evidence that this is also an important factor in determining crash rate. Larger differences in speed between vehicles are related to a higher crash rate. Without exception, a vehicle that moved (much) faster than other traffic around it, had a higher crash rate. With regard to the rate of a (much) slower moving vehicle, the evidence is inconclusive.

Keywords: Driving speed; Speed variance; Crash rate; Literature review

1. Introduction

Speed is an important factor in road safety. Speed not only affects the severity of a crash, but is also related to the risk of being involved in a crash (e.g. Elvik et al., 2004). Once a crash occurs, the relationship between speed and the outcomes of a crash is directly related to the kinetic energy that is released during a collision ($E_k = (1/2)mv^2$) and hence quite straightforward. The relationship between speed and the risk of a crash is much more complex. It is easy to understand that at high speeds the time to react to changes in the environment is shorter, the stopping distance is larger, and manoeuvrability is reduced. However, it is difficult to quantify this relationship unequivocally, since many factors determine to what extent these consequences of a higher speed would affect the crash rate. There are quite a few empirical studies that looked into the speed–crash rate relationship aiming at quantifying the general relationship and the influence of external factors. They often used different research methods as well as different speed measures, which complicates a direct comparison of the results and the understanding of different outcomes. It is the objective of the current review to present and discuss a number of these empirical studies in a systematic way to disentangle the factors that may be responsible for differences in the outcomes, come to a balanced judgement of the most likely conclusions, and, finally, to identify issues that are as yet insufficiently clear and would benefit from further research. The emphasis is on recent studies, but also a small number of older studies with influential results are discussed.

2. Absolute speed and crash rate

Many of the studies into the relationship between speed and crash rate examined absolute speed or found absolute speed to be relevant for crash rates. Some of these studies looked at individual vehicle speeds, others at average road section speeds (Table 1).

2.1. Individual vehicle speed

One way to examine the relationship between speed and crash rate, is to determine the crash liability of individual

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Table 1
Absolute speed and crash rate

Study	Method	Crash measure	Road type(s)	Number of cases	Origin of data	Results
Individual vehicle speed						
Fildes et al. (1991)	Self-report study	Material damage only or more severe in last 5 years	Urban 60 km/h and rural 100 km/h (speed limits). Data of V15 and V85 on each road were used	707 drivers, four road links, two types of roads	Australia	Exponential functions per road type (not specified): the higher the speed, the larger the increase of the crash rate
Maycock et al. (1998)	Self-report study	Material damage only or more severe in last 3 years	All UK road types (not specified; average speed = 52 mph (≈83 km/h))	6435 drivers, 43 road links	UK	$A_{i3} = 0.265\left(\frac{v}{\bar{v}}\right)^{13.1}$
Quimby et al. (1999)	Self-report study	Material damage only or more severe in last 3 years	All UK road types except for highways (not further specified; average speed = 42 mph (≈67 km/h))	4058 drivers with free speed, 24 road links	UK	$A_{i3} = 0.215\left(\frac{v}{\bar{v}}\right)^{7.8}$
Kloeden et al. (1997, 2002)	Case–control study	Hospital admission or more severe	Urban roads, 60 km/h (speed limit)	151 cases, 604 controls	Australia	Urban roads with speed limit of 60 km/h: $I_r = \exp(0.1133374\Delta v + 0.0028272v^2)$
Kloeden et al. (2001)	Case–control study	Hospital admission or more severe	Rural roads, 80–120 km/h (speed limit)	83 cases, 830 controls	Australia	Rural roads with speed limits of 80–120 km/h: $I_r = \exp(0.07039\Delta v + 0.0008617v^2)$
Average speed at road section level						
Nilsson (1982, 2004)	Before–after study	Police reported crashes of different severities	90–110 km/h (speed limit)	–	Sweden	Crash rate: $A_2 = A_1\left(\frac{v_2}{v_1}\right)^2$, injury rate: $I_2 = I_1\left(\frac{v_2}{v_1}\right)^3$, fatality rate: $F_2 = F_1\left(\frac{v_2}{v_1}\right)^4$
Finch et al. (1994)	Meta-analysis of before–after studies	–	30–120 km/h (speed limit)	13 studies for fitting the model (but more studies are discussed)	Finland, United States, Switzerland, Denmark	$\Delta A = 4.92\Delta\bar{v}_{\mathrm{mph}}$ and $\Delta A = \left[\frac{53.40}{1+\exp(-0.58\Delta\bar{v}_{\mathrm{mph}})}\right] - 25.09$
Baruya (1998a, 1998b)	International cross-sectional study	–	Rural single carriageway roads, 70–110 km/h (speed limit)	171 road links	Sweden, UK, The Netherlands	$A_r = (C_{\mathrm{road}})\bar{v}^{-2.492}o_{v_{\mathrm{limit}}}^{0.114}$ with $C_{\mathrm{road}} = 5.663\mathrm{fl}^{0.748}l^{0.847}\exp(0.038j - 0.056w + 0.023v_{\mathrm{limit}})\exp(0.023v_{\mathrm{limit}})$

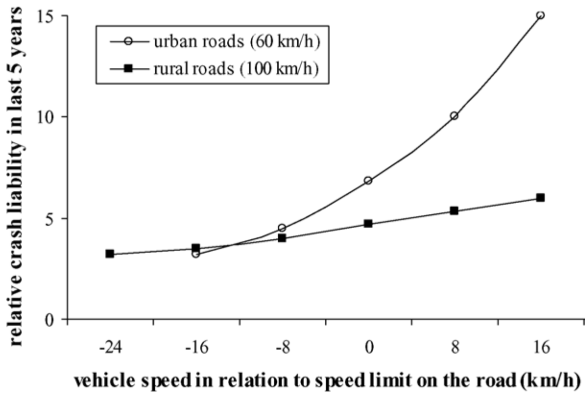

Fig. 1. The relation between speed and crash rate on urban 60 km/h and rural 100 km/h roads according to Fildes et al. (1991).

vehicles that drive at different speeds. Self-report studies and case–control studies are the most common approaches here.

In self-report studies the measured speed of an individual vehicle is linked to the number of self-reported crashes of the driver. An Australian study by Fildes et al. (1991) applied a self-report method. This study was performed on two urban 60 km/h roads and two rural 100 km/h roads. Fildes et al. collected speed data and selected those drivers who drove at a speed below V15 (slow drivers) or above V85 (fast drivers) of the traffic speed distribution. Selected drivers were stopped out of sight of the speed measurement location and were asked about their history of road crashes during the last 5 years. Fast drivers had had more crashes in the last 5 years than the slow drivers. For both the urban and the rural roads, the relationship had the shape of an exponential function, which was much steeper for urban roads than for rural roads (Fig. 1). General drawbacks of this self-report method are that the measured speed may not be representative for the speed that was maintained before the crash. Furthermore, per definition, only crashes that the driver survived can be included and there is no control for confounding variables. Specific weak points of the study of Fildes et al. are (a) the small number of locations (two per road type) and (b) the small number of days of measurement (4–6 days per location).

In the UK, Maycock et al. (1998) and Quimby et al. (1999) also applied the self-report method. Both studies had a similar design, and found a similar pattern of increase in crash liability with increasing speed. At a more detailed level however, the method and the results differed. Maycock et al. inconspicuously measured the speed of 6435 vehicles with a laser gun on 43 roads. The measured speeds were classified in one of five equal percentile bands of the total traffic speed distribution. Within each band, an identical number of vehicles were randomly selected. The drivers of the selected vehicles received a questionnaire to get information about their crash history (46% response rate). The researchers found the following mathematical function (see Table 2 for the meaning

Table 2
Meaning of the equation variables

Variable coding	Meaning
A_1	Number of (police reported) injury crashes before change
A_2	Number of (police reported) injury crashes after change
A_{i3}	Self reported crash liability in last 3 years
A_r	Frequency of injury crashes
ΔA	Relative difference in crash rate as a result of the change in speed limit
E_k	Kinetic energy
F_1	Number of (police reported) fatal crashes before change
F_2	Number of (police reported) fatal crashes after change
fl	Traffic flow (average amount of daily traffic)
I_1	Number of (police reported) injury crashes before change
I_2	Number of (police reported) injury crashes after change
I_r	Injury crash rate
j	Number of junctions per road section
l	Length of the road section (km)
m	Mass
$o_{v_{\text{limit}}}$	Proportion speed limit offenders
SD	Standard deviation of the traffic speed
v	Individual vehicle speed
$\bar{v}$	Average speed
Δv	Difference between individual vehicle speed and average traffic speed
$\Delta\bar{v}$	Realised change in average traffic speed
v_{limit}	Speed limit
v_1	Average speed before change
v_2	Average speed after change
w	Width of the road lanes (m)

Speeds are in km/h, unless indicated otherwise.

of the variables in each of the equations):

$$A_{i3} = 0.265\left(\frac{v}{\bar{v}}\right)^{13.1} \quad (1)$$

They translated this function in the rule of thumb that 1% increase in speed is related to a 13.1% increase in crash liability.

In contrast to the study of Maycock et al., Quimby et al. (1999) only included speed and crash data of drivers who had a free driving speed (defined as a distance of at least 3 s to the vehicle in front) on roads except motorways. As in the study of Maycock et al., vehicles were selected randomly from five percentile bands of the speed distribution of 24 roads. Based on the questionnaire response about crash liability of 4058 identified drivers (43% response rate), Quimby et al. found the following function:

$$A_{i3} = 0.215\left(\frac{v}{\bar{v}}\right)^{7.8} \quad (2)$$

They concluded from this function that a 1% increase in free speed is related to an increase of 7.8% in crash liability. The results of both studies are graphically depicted in Fig. 2.

Quimby et al. found a smaller increase of crash liability with increasing speed than Maycock et al., which may be related to the few differences between the two studies and the resulting differences in average speed: 42 mph (≈67 km/h) in the study of Quimby et al., and 52 mph (≈83 km/h) in the

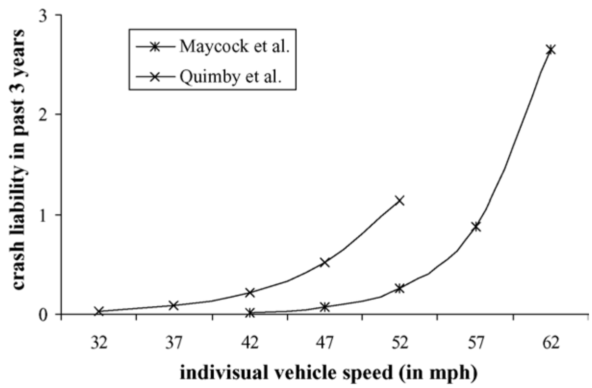

Fig. 2. The relationship between individual vehicle speed and crash liability in the last 3 years as found in the studies of Maycock et al. (1998) and Quimby et al. (1999).

study of Maycock et al. In addition to the general drawbacks of self-report studies, a possible weak point in these two studies was the relatively low response rate to the questionnaires, which may have biased the results. Another point that has to be mentioned is the transformation of the power number into a percentage number in the rules of thumb. This may be approximately correct for very small increases or decreases in speed, but not for larger ones.

The other method to examine the relationship between individual speed and crash involvement is the case–control study. In a case–control study the (estimated) pre-crash speeds of crash-involved vehicles (cases) are linked to the speeds of vehicles (controls) that were not involved in a crash and drove under comparable conditions. In Australia, Kloeden et al. (1997) applied the case–control method to examine the relationship between driving speed and crash rate on urban roads with a speed limit of 60 km/h. In this study, 151 cases were linked to 604 control vehicles. The free pre-crash speed of the case vehicles was reconstructed by experts using physical marks and computer speed-reconstruction programmes. Since the case vehicles had to be at the crash location long enough to reconstruct the pre-crash speed, only serious crashes could be taken into account. The case and control vehicles were matched for factors such as driving direction, driving area, time of day, weather, light intensity, vehicle type, etc. Reanalysis of the data (Kloeden et al., 2002) revealed the following exponential function between speed of an individual vehicle and his risk of an injury crash on urban roads:

$$I_r = \exp(0.1133374\Delta v + 0.0028272v^2) \tag{3a}$$

In a similar second study, Kloeden et al. (2001) examined the speed–crash rate relationship on rural roads with speed limits between 80 and 120 km/h. In this study, each of the 83 cases was linked to 10 control vehicles ($n = 830$). For these roads, they found the following exponential function:

$$I_r = \exp(0.07039\Delta v + 0.0008617v^2) \tag{3b}$$

These results indicate that on urban roads the crash rate increases more with increasing speed than on rural roads. In principle, these functions reflect a relatively pure relationship between speed and crash rate because many factors were controlled. A possible weak point, inevitably linked to the case–control approach, is the reconstruction of the pre-crash speeds of the case vehicles.

Overlooking the results of these studies, they all come to the conclusion that fast moving vehicles have a larger crash rate than slow moving vehicles. Maycock et al. (1998) and Quimby et al. (1999) reported a power function to describe the relationship, whereas Fildes et al. (1991) and Kloeden et al. (1997, 2001) reported an exponential function. These latter three studies also found that the crash rate increases faster with increasing speed on urban than on rural roads. Methodological differences, differences in the operationalisation of variables, and the influence of coincidental factors, all may account for differences in results at a detailed level.

2.2. *Average speed at road section level*

The relationship between driving speed and crash rate has also been assessed by linking the average traffic speed at a road to the crash rate of that road. Frequently used methods for this approach are before–after studies and cross-sectional studies.

Before–after studies typically link the average speed and crash rate before a speed management measure (e.g. a speed limit change or speed enforcement) to the average speed and crash rate after. In order to control for the effect of other factors than speed (e.g. changes in traffic volume), a comparable control group must be included.

The often cited study of Nilsson (1982) is a good example of a before–after study. Nilsson evaluated the safety effects on Swedish rural roads after changing the speed limit from 110 to 90 km/h and vice versa. Roads with an unchanged speed limit of 90 km/h were used as control locations. It was found that a speed limit reduction was accompanied by a reduction in average speed as well as a reduction in the number of crashes. To describe the change in the number of police reported crashes due to changes in speed, Nilsson adapted the formula for kinetic energy ($E_k = (1/2)mv^2$) with the notion that only speed changes and the effect of mass can be eliminated:

$$A_2 = A_1 \left(\frac{v_2}{v_1}\right)^2 \tag{4a}$$

Subsequently, Nilsson reasoned that the number of severe crashes would increase faster with an increase in speed than the overall number of crashes and thus had to be estimated with a larger power. He used Eq. (4a) as a basis and increased the power of the function to calculate the relative change in severe injury crashes:

$$I_2 = I_1 \left(\frac{v_2}{v_1}\right)^3 \tag{4b}$$

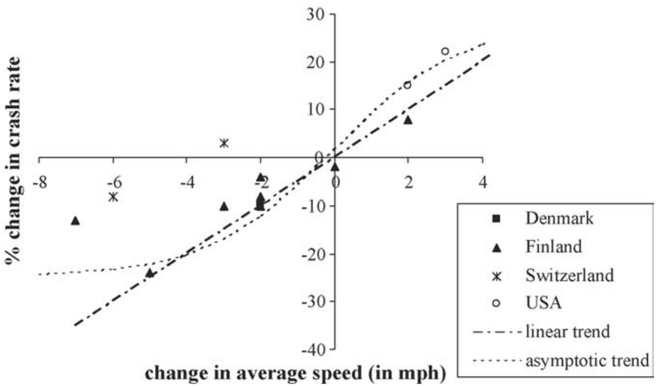

Fig. 3. 'Linear' and asymptotic relation between changes in average traffic speed and change in crash rate according to a meta-analysis of Finch et al. (1994).

and fatal crashes:

$$F_2 = F_1\left(\frac{v_2}{v_1}\right)^4 \tag{4c}$$

It is remarkable that Nilsson described the relationship between average speed and crash rate (Eq. (4a)) by using the formula for kinetic energy, which is particularly related to crash severity. Nilsson (2004) added that the power functions include an indication of the increase in braking distance to avoid a crash when driving at a higher speed. A regression meta-analysis of a large number of before–after and cross-sectional studies (Nilsson, 2004; Elvik et al., 2004) showed that the outcomes of speed limit changes on both rural and urban roads could very well be described by the three power functions. The researchers concluded that these power functions are reliable for the prediction of crash rate changes due to changes in average speed.

Also, Finch et al. (1994) performed a meta-analysis on data of average speed and crash rate before and after speed limit changes on main rural roads in Finland, Denmark, Switzerland, and the United States. They fitted three different functions on the data: (1) a linear function, (2) one of Nilsson's power functions, and (3) an asymptotic function. As a 'linear' function, they found:

$$\Delta A = 4.92\Delta\bar{v}_{\text{mph}} \tag{5a}$$

As a rule of thumb, the researchers stated that a speed reduction of 1 mph corresponded with a 5% decrease in crash rate (1 km/h with 3%; Fig. 3). The Nilsson-function (probably Eq. (4b)) also fitted the data well. Finally, they tried to fit an asymptotic function because they reasoned that speed is not a cause in all crashes and, consequently, changes in speed would only have a limited effect on road safety. They found the following function to fit best:

$$\Delta A = \left[\frac{53.40}{1+\exp(-0.58\Delta\bar{v}_{\text{mph}})}\right] - 25.09 \tag{5b}$$

This function shows that the maximum increase in crash rate due to an increase in speed is 28% and the maximum decrease in crash rate due to a decrease in speed is 25% (Fig. 3). Although all three functions fitted well, Finch et al. preferred to present Eq. (5a) as the main result.

Table 3
The outcomes from the three power functions of Nilsson (1982, 2004) when average speed changes with 1 km/h

Percentage change in crashes						
Crash severity	Reference speed (in km/h)					
	50	70	80	90	100	120
Injury crashes (%) (Eq. (4a))	4.0	2.9	2.5	2.2	2.0	1.7
Injury and fatal crashes (%) (Eq. (4b))	6.1	4.3	3.8	3.4	3.0	2.5
Fatal crashes (%) (Eq. (4c))	8.2	5.9	5.1	4.5	4.1	3.3

As indicated by the researchers themselves, countries differ in the scope they have for road safety improvements. In addition, several unknown factors could have affected speed as well. Furthermore, the effects of speed limit changes on average speed and crash rate may be different depending on the time period that elapsed between the before and after measurement of a study. We may add the following comments: Eq. (5a) shows that, between two points of measurement, the increase or decrease in relative crash rate is always approximately the amount of change in speed (in km/h) multiplied by a factor 3, independent of the reference speed. The rule of thumb, however, can be applied in another way as well, namely by multiplying the new crash rate of every km/h change in speed with 3%, which would result in a power-like function. As nearly all data points are located above the linear trend line of Eq. (5a), this could indicate that such a curvilinear function would fit the data better. Furthermore, it is very implausible that a reduction of 1 km/h in average speed always results in an equal reduction in crash rate for different reference speeds (see also Elvik et al., 2004). If we look at the second power function of Nilsson (Eq. (4b)), it appears that a 1 km/h change in speed only coincides with an approximate change of 3% in crash rate if the reference speed is between 90 and 120 km/h (Table 3). These are exactly the speeds that are common on main rural roads, which were included in the meta-analysis of Finch et al. For roads with a lower reference speed, the 3%-rule underestimates the change in crash rate with a change in speed. Finally, the asymptotic result (Eq. (5b)) can be commented on. Although the low asymptote may be inspired by the collected data points, a theoretical basis for the asymptotic values is missing.

Baruya (1998a) performed a cross-sectional study to assess the relationship between average speed and crash frequency. Cross-sectional studies compare different characteristics of different roads, including average speed, to determine the amount of variance in crash frequency that they explain.

Baruya reanalysed the speed and injury crash data of 139 Dutch, British and Swedish rural single carriageways with a speed limit between 70 and 110 km/h (or mph equivalents). Speed data had been collected during off-peak periods. Flow data was based on 24 h data. Baruya found the following power function to describe the relationship between average speed and injury crash frequency:

$$A_r = 5.663\text{fl}^{0.748} l^{0.847} \exp(0.038 j - 0.056 w + 0.023 v_{\text{limit}}) \times \exp(0.023 v_{\text{limit}}) \bar{v}^{-2.492} o_{v_{\text{limit}}}^{0.114} \quad (6)$$

In words, this function shows that, for the roads included in the analysis: (1) the crash frequency is affected most by traffic flow (a convex increase with increasing flow); (2) a higher speed limit coincides with a higher crash frequency. It must be noted that Baruya analysed only one road type (rural single carriageways), which could have higher or lower speed limits with a relatively similar road design. (3) An increase in the proportion of speed limit offenders is related to an increase in crash frequency (convex increase); (4) roads with a larger junction density have higher crash frequencies; (5) longer sections of road have a higher crash frequency. (6) Roads with narrow lanes have a higher crash frequency (concurve increase) and, finally, (7) the crash frequency increases more with lower average speed. This last finding contradicts that of other studies and is also in contradiction to Baruya's own summarising finding that 1 km/h decrease in speed is related to 1.5–3% decrease in crash frequency. This discrepancy may be explained by the fact that the factors that were examined by Baruya, do not stand alone, but interact with each other. Narrower roads and a larger junction density, for instance, may result in a lower average speed, but in a higher crash frequency. The relationships can therefore only be understood as a whole. A cross sectional approach does not allow to assess the effect of an isolated variable.

Another point may be that the different speed limits that were included in the Baruya study came from different countries (Baruya, 1998b). Therefore, it cannot be excluded that national differences in, for example, traffic composition or elements of road design, interfered with the crash frequency for different speeds. The fact that the model did not fit Portugese data (Baruya, 1998a) is another indication that the results may only be applicable to the included countries and road types. Furthermore, it must be noted that the speed data of off-peak periods were linked to the traffic flow and crashes of a 24-h period. This may have resulted in an overestimation of the average speed on a road and, hence, an underestimation of the effect of speed. Comparing Baruya's findings with those of Finch et al. (see Eq. (5a)) and Nilsson's second power function (see Table 3), Baruya finds a somewhat smaller effect of speed changes on the amount of crashes for more or less similar road types.

Summarising, as with studies into individual vehicle speed, most studies that examined effect of average speed at a road concluded that crash rate increases when speed increases. This relationship can be described by a power function (Finch et al., 1994; Nilsson, 1982, 2004), although also alternative functions or interpretation of functions (i.e. linear or asymptotic) were reported (Finch et al.). Furthermore, as with individual vehicle speed, an increase in average speed was found to increase the risk of a crash more on minor than on major roads (Nilsson, 2004), which are linked to particular speed limit bands. On a more detailed level, the study of Baruya (1998) provided a more complex mathematical description of how crash frequency is related to a number of average speed measurements, and road and traffic characteristics.

3. Speed dispersion and crash rate

Not only absolute speed, but also speed dispersion has been found to relate to crash rate. As for absolute speed, a distinction must be made between studies that examined the contribution of speed differences between individual vehicles to crash rate and studies that examined the influence of speed variance at road section level (Table 4).

3.1. Speed differences between individual vehicles

Studies into differences in individual vehicle speed and their crash rates mainly use a case–control approach. A very old, but often cited study in this category is that of Solomon (1964). For main rural highways (USA), Solomon compared the estimated speed of 10,000 case vehicles that had been involved in a (police reported) crash and the measured speed of 29,000 control vehicles. The speed estimates of the case vehicles were based on notes about speed in the police reports. The speed of the control vehicles was measured alongside the roads on different moments of the day. The modus speed on a road was established by driving with the traffic flow and sampling this speed. Solomon calculated the relative crash rates in relation to vehicle speed by comparing the crash proportion per speed category (defined in classes of 10 mph (≈16 km/h)). He found that vehicles moving approximately 6 mph (≈10 km/h) faster than the modus speed had the lowest crash rate. Vehicles moving much faster or much slower (i.e. >50 km/h) than the modus speed had a substantial higher crash rate. This resulted in the well-known U-curve.

A few years later, Cirillo (1968) replicated the study of Solomon on rural and urban interstate roads (USA). Cirillo only analysed crashes between two or more vehicles that moved (more or less) in the same direction. Furthermore, she calculated the total percentage of vehicles involved in a crash rather than the crash proportion per speed category. Despite these differences with the study of Solomon, she found a very similar pattern in the relationship between speed differences and crash rate, but with the lowest crash rate for vehicles moving approximately 12 mph (≈20 km/h) faster than the modus speed.

Improvements of (speed) measurement equipment inspired the researchers of the US Research Triangle Institute to replicate these previous speed–crash rate studies (RTI, 1970). Using physical marks and speed estimates of people involved, the RTI reconstructed the pre-crash speed of 200 crash-involved vehicles. The speed of control vehicles was determined by using speed detection loops. The crash rate was calculated in the same way as was done by Solomon.

Table 4
Speed dispersion and crash rate

Study	Method	Crash measure	Road type(s)	Number of cases	Origin of data	Results
Speed differences between individual vehicles						
Solomon (1964)	Case–control study	Material damage only or more severe	Rural highways, 35–70 mph (design speed (≈56–112 km/h)), 45–70 mph (speed limit (≈72–112 km/h))	10,000 cases, 29,000 controls	USA	U-shaped curve: drivers with a speed higher or lower than 6 mph (≈10 km/h) above the modus speed have an increased rate of crash involvement
Cirillo (1968)	Case–control study	Material damage only or more severe	Rural and urban interstate roads, 40–80 mph (speed limit (≈64–128 km/h))	–	USA	U-shaped curve like Solomon but steeper for slow drivers and with a lower crash rate for drivers with speed 12 mph (≈20 km/h) above the modus speed
RTI (1970)	Case–control	–	40 mph (≈64 km/h) and more (speed limit)	200 cases	USA	U-shaped curve but much flatter than the curves of Solomon and Cirillo.
Kloeden et al. (1997, 2001)	Case–control study	Hospital admission or more severe	Urban 60 km/h and rural 80–120 km/h (speed limits)	234 cases, 1434 linked controls	Australia	Exponential functions per road type (see Table 1).
Speed differences at road section level						
Garber and Gadiraju (1989)	Cross-sectional study	Material damage only or more severe	Interstate roads, arterial roads, and rural major collector roads, 55 mph (speed limit (≈88 km/h))	124 crashes, 36 road links	USA	Large traffic speed variance is related with higher crash rates. Traffic speed variance is mostly lower on roads with a high speed limit
Taylor et al. (2000)	Cross-sectional study	Hospital admission or more severe	Urban single carriageways, 30 or 40 mph (speed limit)	300 road links, 1590 crashes	UK	$A_r = (0.000435\bar{v}_{\mathrm{mph}}^{-2.252}) \exp\left(5.893 \frac{SD_{\mathrm{mph}}}{\bar{v}_{\mathrm{mph}}}\right)$

Again, the result was a U-shaped function between speed and crash rate. However, the RTI found that 44% of the analysed crashes concerned manoeuvres, which, by definition, involve low speed. Reanalysis of the data without the manoeuvre crashes showed that the increased risk of slow driving vehicles was much lower than indicated by the results of Solomon and Cirillo.

The major weak points of these old studies are the inaccurate speed estimates and the lack of matches between other characteristics of the case and control vehicles (see also Shinar, 1998). A more recent case–control study that examined the crash involvement risk of slow and fast driving vehicles more accurately, are the Australian studies of Kloeden et al. (1997, 2001; see 2.1). These studies found an increased risk for vehicles moving faster than the others, but not for vehicles moving slower.

In conclusion, it can be stated that both the older and the more recent studies provide evidence that driving faster than the surrounding traffic increases the risk of a crash. With regard to driving slower than average, the evidence is less conclusive. Older studies (Solomon, 1964; Cirillo, 1968; RTI, 1970) found an increased risk, but more recent studies (Kloeden et al., 1997, 2001) did not.

3.2. Speed differences at road section level

Another way to relate crash rate to speed dispersion is to look at speed differences at road section level, i.e. the speed variance. In the eighties, Garber and Gadiraju (1989) performed a cross-sectional study in which they examined the relationship between crash rate and different speed measures, including speed variance. Their study included three types of 55 mph (≈90 km/h) limit roads in the USA: interstate roads, arterial roads, and major rural collector roads. They measured spot vehicle speeds and 24 h traffic flow during weekdays, and linked these to the 124 crashes that had occurred on the examined roads in the last 3 years. They found that roads with a larger speed variance had a higher crash rate than roads with a smaller speed variance. Contrary to the findings of most other studies, Garber and Gadiraju found a negative relationship between average speed and crash rate at the examined roads. However, large speed variances appeared to be associated with relatively low average traffic speeds.

Garber and Gadiraju also found that the difference between design speed and speed limit plays a role. Although all examined roads had the same speed limit, their design speed varied from 40 to 70 mph (≈64–112 km/h). Average speed mainly corresponded to the design speed. Garber and Gadiraju found that the crash rate and speed variance was lowest when the speed limit was 5–10 mph (≈8–16 km/h) lower than the design speed.

More recently, Taylor et al. (2000) also found that traffic speed variance is related to the crash frequency. They collected aggregated 24 h spot speed data of 300 urban single carriageway roads in the UK and linked this to 1590 injury crashes at these roads. The researchers distinguished four

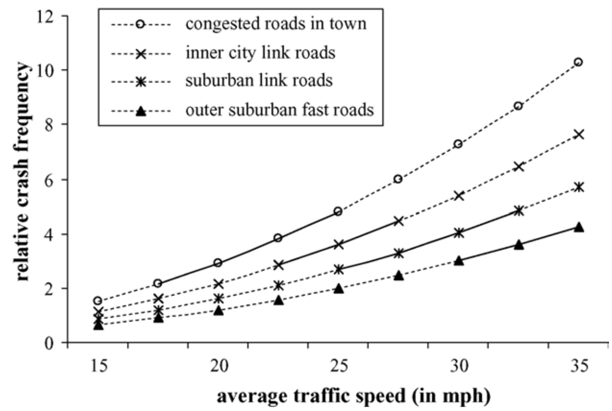

Fig. 4. The relationship between average speed and crash frequency on four urban road types (Taylor et al., 2000). The dotted lines reflect the extrapolation of the observed data, based on the speed–crash rate according to Eq. (7).

road types: congested roads in town, inner city link roads, suburban link roads, and outer suburban fast roads. The results show that for each of these road types the crash frequency increased more with increasing average speed. At a more detailed level, congested roads both had a higher absolute crash frequency and a larger increase in crash frequency with higher average speeds than fast roads (Fig. 4). As in the Garber and Gadiraju study, lower average speeds coincide with a larger speed variance and both were found to be related to crash frequency in the following way:

$$A_r = (0.000435\bar{v}_{\mathrm{mph}}^{-2.252}) \exp\left(5.893\frac{SD_{\mathrm{mph}}}{\bar{v}_{\mathrm{mph}}}\right) \tag{7}$$

In conclusion, the studies that examined speed variance at road section level all found that larger speed variance is related to a higher crash rate. They also found that high average speeds are related to low speed variance.

4. Conclusion and discussion

The current review of empirical studies into the relationship between speed and the risk of a crash shows that, at a particular road, the crash rate increases when speed increases. This has been found in two different ways: on individual vehicle level and at road section level.

Recent studies that examined the relation between individual vehicle speed and crash rate mainly used self-report methods (Fildes et al., 1991; Maycock et al., 1998; Quimby et al., 1999) or case–control methods (Kloeden et al., 1997, 2001). Although both self-report studies and case–control studies have drawbacks, we consider case–control studies as superior for the examination of the relationship between speed and crash rate since they can control for many confounding factors. Therefore, we may conclude that, for now, the results of Kloeden et al. best describe the relationship between individual vehicle speed and crash rate. This means that crash rate rises exponentially for individual vehicles that increase their speed. Furthermore, crash rate increases faster with a particular increase in speed on minor/urban roads than on major/rural roads.

None of these relatively recent studies found evidence that also vehicles that move (much) slower than the surrounding traffic have an increased crash rate. In earlier studies, vehicles with a (much) higher speed as well as a (much) lower speed than the modus speed on the road were found to have an increased crash rate (Solomon, 1964; Cirillo, 1968; RTI, 1970). Theoretically, this result is plausible, as deviation from the modus traffic speed increases the likelihood of an encounter and, hence, of a crash with traffic on the same roadway (Elvik et al., 2004; Hauer, 1971; Shinar, 1998). These different findings may be due to the better equipment to measure and reconstruct vehicle speeds and a more sound research design of the recent studies compared to the older ones. Hence, the recent results may be considered as more reliable. Another explanation is that the older studies included manoeuvring vehicles in their analyses (with exception of the second RTI analysis), whereas the recent studies did not. Since manoeuvring is likely to contain other risks than just those related to (low) speeds, it is preferable to exclude manoeuvring vehicles from analyses that aim to assess the pure speed–crash rate relationship (e.g. Kloeden et al., 1997; Shinar, 1998). A third, fairly speculative explanation is that the different findings of the older and newer studies reflect a real difference, related to a change in traffic and traffic conditions over time. Compared to 35 years ago, low speeds may be less dangerous these days (see also Shinar, 1998) or extreme deviations in speed, especially towards the lower end of the speed distribution, may be less common. Based on this review, it is impossible to give a decisive answer.

A second way to examine the relationship between speed and crash rate is by comparing crash rate with mean speed at road section level. As the power functions of Nilsson were extensively evaluated (Nilsson, 2004; Elvik et al., 2004) and fitted the speed and crash data of very different road types, we consider that these functions describe this relationship best. They are based on a fairly sound before–after study design and describe the effect of changes in average speed on different crash severities levels. To present a power function as a rule of thumb, not only changes in crash rate but also the change in speed has to be presented as a percentage. For Nilsson's power functions, this would mean: 1% increase in speed results approximately in 2% change in injury crash rate, 3% change in severe crash rate, and 4% change in fatal crash rate. Clearly, this is still a rule of thumb. It must be noted that the presentation of the speed change as a percentage means that the absolute change in speed required to reach a particular effect is larger on higher speed roads (e.g. motorways) than on lower speed roads (e.g. urban roads). If the change in speed is presented as an absolute number, such as in the rule of thumb of Finch et al., there is no difference in results for the same absolute change in speed on roads with different speed designs.

Still, the exact relationship between speed and crash frequency depends on the actual road and traffic characteristics (e.g. Baruya, 1998a, 1998b), including road width, junction density, and traffic flow. These are most likely mediating factors in that they both affect the crash frequency directly and by their effect on speed. The interaction of factors may explain why Baruya found that low speeds were related to high crash frequency. As Baruya did, a cross-sectional research method is the appropriate research method to describe the interaction of all these variables, but this method does not allow to assess the relative effects of the variables in isolation.

The review also showed that, in addition to average speed, large speed variance at a particular road is related to high crash rates (e.g. Garber and Gadiraju, 1989; Taylor et al., 2000). However, (see also Shinar, 1998), it is hard to understand the exact meaning of this relationship because the speed variance in most studies reflects the range in speed over 24 h on road. This means that the speed variance may be dominated by the difference in traffic speed between peak and off-peak periods rather than by differences in speed between vehicles at a particular moment, and thus reflects differences in speed as a result of the amount of traffic on a road. There is no theoretical explanation why large differences in speeds between peak- and off-peak periods should be related to high crash rates. At a more detailed level, however, it is known that large traffic flows both reduce speed and increase the risk of a crash (e.g. Elvik et al., 2004). To understand the relationship, it would be better to examine speed and crash data on a more disaggregated level. Furthermore, speed variance may also be related to traffic composition (e.g. the proportion of heavy vehicles or the presence of vulnerable road users) and the interaction between different road user groups. The studies discussed in this review mainly examined point measurements on which they based their measures for speed deviation, but also longitudinal speed differences of vehicles over a stretch of road, for example related to longitudinal design consistency, may be a factor of importance (Krammes and Glascock, 1992; Lamm et al., 2000). The issue of speed deviation certainly is an area that would need more extensive examination if we want to understand and to quantify its effect on road safety.

Both individual vehicle studies and studies at road section level found that the crash rates increase faster with an increase at roads designed for lower speed than at roads designed for higher speed. This finding not only holds for the major distinction between urban and rural roads (Fildes et al., 1991; Kloeden et al., 1997, 2001; Nilsson, 2004), but also for subtypes of roads (Taylor et al., 2000). It is very likely that this is directly related to the amount of traffic interaction and traffic composition on these types of road but also the design of the road (e.g. Baruya, 1998a). Whereas it is clear that all sorts of road and traffic characteristics play an important role, we still know insufficiently which ones exactly, to what extent and how they interact.

A final remark do we have to make on the operationalisation of what we call 'crash rate' in this review. To mention some common operationalisations: crash liability of drivers in the last 3 or 5 years, crash frequency (which is actually no crash rate), crash frequency per speed category, or crash frequency per kilometre road length. These different operationalisations of 'crash rate' are a complicating factor in the comparison of the results of studies. Furthermore, as not all studies are as explicit about their operationalisation as would be preferable for more insight, this is a point of improvement for future studies.

In conclusion, the exact relationship between speed and crash rate depends on a large number of different factors. Even though recent studies shed some light on these factors as well as on the direction of the effects, knowledge is still insufficient to allow for specific quantifications. Researchers must be aware of the influence of external factors on the relationship between speed and crash rate, and be explicit and precise about the external circumstances to which their results apply to.

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