Updated estimates of the relationship between speed and road safety at the aggregate and individual levels

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ABSTRACT

Recent studies of the relationship between the speed of traffic and road safety, stated

as the number of fatalities and the number of injury accidents, are reviewed and their

results synthesised by means of meta-analysis. All studies were based on data fully or

partly for years after 2000. Previously proposed models of the relationship between

the speed of traffic and road safety, including the Power Model and an Exponential

Model, are supported. Summary estimates of coefficients show that the relationship

between speed and road safety remains strong. The Power Model and the

Exponential Model both fit the data very well. The relationship between speed and

road safety is the same at the individual driver level as at the aggregate level referring

to the mean speed of traffic.

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1 INTRODUCTION

The relationship between the speed of traffic and road safety has been the subject of extensive research, see reviews of this research by Elvik (2005, 2013A), Aarts and van Schagen (2006) and the International Transport Forum (ITF) (2018). It is widely accepted that speed limits and their enforcement are effective road safety measures. Nevertheless, raising speed limits is often a popular measure. Speed limits on some roads have been raised after 2000 in, for example, Denmark (ITF 2018), Hungary (ITF 2018), Israel (ITF 2018), Norway, and Sweden (Vadeby and Forsman 2018). In France and Sweden, the speed limit on rural two-lane roads has been lowered from 90 to 80 km/h.

One may ask: Is speed still as important for road safety as it was in the past? Can new vehicle safety systems have made speed less important? Modern cars are better equipped both to avoid accidents and make them less serious (by protecting occupants better) than cars were 15-20 years ago (Høye 2017). On the other hand, their speed performance has increased.

The first objective of this paper is to review evidence concerning the relationship between the speed of traffic and road safety based on studies published after 2000 and in which parts or all of the data refer to the period after 2000. The main question is whether the relationship between speed and road safety, as described mathematically in terms of the Power model (Nilsson 2004) or the exponential model (Elvik 2013A), remains as strong as previous studies have indicated. The second objective is to assess whether the relationship between speed and accident involvement at the individual level, i.e. the relationship between a driver's speed and

his or her accident involvement rate, has the same shape and strength as the aggregate relationship between the mean speed of traffic and the number of accidents or accident victims.

The term "crash" is often used in current road safety studies. We use the term "accident", as we do not find the arguments for avoiding that term (see e.g. Davis and Pless 2001) convincing.

2 PREVIOUS REVIEWS

Elvik (2005) summarised the main findings of the review of Elvik, Christensen and Amundsen (2004). The paper evaluated the Power Model of the relationship between the mean speed of traffic and road safety, stating that changes in speed are related to changes in safety in terms of a set of power functions:

$$\text{Number of fatal accidents} = Y_1 = \left(\frac{V_1}{V_0}\right)^4 Y_0 \tag{1}$$

$$\text{Number of fatalities} = Z_1 = \left(\frac{V_1}{V_0}\right)^4 Y_0 + \left(\frac{V_1}{V_0}\right)^8 (Z_0 - Y_0) \tag{2}$$

$$\text{Number of fatal and serious injury accidents} = Y_1 = \left(\frac{V_1}{V_0}\right)^3 Y_0 \tag{3}$$

Number of fatal or serious injuries = $Z_1 = \left(\dfrac{V_1}{V_0}\right)^3 Y_0 + \left(\dfrac{V_1}{V_0}\right)^6 (Z_0 - Y_0)$ (4)

Number of injury accidents (all) = $Y_1 = \left(\dfrac{V_1}{V_0}\right)^2 Y_0$ (5)

Number of injured road users (all) = $Z_1 = \left(\dfrac{V_1}{V_0}\right)^2 Y_0 + \left(\dfrac{V_1}{V_0}\right)^4 (Z_0 - Y_0)$ (6)

V_1 is speed after a change. V_0 is speed before a change. Y_1 is the number of accidents after a change in speed, Y_0 is the number of accidents before a change in speed. Z_1 is the number of killed or injured road users after a change in speed, Z_0 is the number of killed or injured road users before a change of speed. Based on the laws of physics, Nilsson (2004) proposed specific values for the exponents. The evaluation of the model determined values of the exponents empirically. Empirical estimates were in general close to the exponents proposed by Nilsson (2004).

Aarts and van Schagen (2006) reviewed studies of driving speed and the risk of accidents. Their review included both studies of the relationship between an individual driver's speed and his or her involvement in accidents and studies of the mean speed of traffic and the number of accidents on road sections. The relationship between speed variance and safety was also discussed. They note that all studies find that increased speed is associated with an increased risk of accidents, but that the exact shape of the relationship may vary according to the type of traffic environment. An interesting issue not discussed in the paper is whether the relationship between

speed and accident involvement has the same shape and strength at the individual level (i.e. the relationship between a driver's speed and his/her accident rate) as at the aggregate level. This issue will be discussed later in this paper.

Elvik (2013A), inspired by a re-analysis of Elvik, Christensen and Amundsen (2004) by Hauer and Bonneson (2006), compared two models of the relationship between speed and road safety: (1) The Power Model (presented above) and (2) An exponential model. The main differences between the two models can be explained as follows. According to the Power Model, the estimated effect of a given relative change in speed is independent of initial speed. Thus, a reduction from 30 to 20 km/h would have the same effect on the number of fatalities as a reduction from 90 to 60 km/h. According to the exponential model, the effect of a change in speed depends on the difference in speed before and after a change:

$$Y_1 = Y_0\, e^{(\beta\,(v_1 - v_o))} \tag{7}$$

A change from 90 to 60 km/h would have a three times larger effect than a change from 30 to 20 km/h. In keeping with the notation for the Power model, Y denotes accidents, V denotes speed, subscript 1 after a change in speed and subscript 0 before a change in speed. When fitting equation 7 to data, it contains a constant term. This has been omitted from equation 7, as only the speed coefficient is applied when using the equation to estimate effects of changes in speed. Elvik (2013A) found that both the Power model and the Exponential model fitted the data very well.

The most recent review of the relationship between speed and safety is the ITF-report (ITF 2018). The report contains a set of case studies of changes in speed limits

or enforcement of speed limits. These studies are from many countries. The report concludes that the results found in the case studies are consistent both with the Power model and the Exponential model, although no formal test of which model best fits the data is reported. The number of case reports included in the ITF-report was too small for a meta-analysis to make sense. In this paper, therefore, the studies presented in the ITF-report have been supplemented by other recent studies of the relationship between speed and road safety.

3 STUDY RETRIEVAL AND INCLUSION

In addition to the studies presented in the ITF-report (ITF 2018), relevant studies were identified by a search of Sciencedirect, using "speed" AND "road safety" as search terms. Some studies have been published both in the ITF-report and as journal papers or research reports (Cunningham et al. 2005, Elvik 2013B, Vadeby and Forsman 2018). The reports and journal papers have then been used as the main source, since they contain more details than the ITF-report. Studies were included if they satisfied the following criteria:

1. The mean speed of traffic before and after a change resulting from an intervention was reported,

2. The intervention influencing speed was either: (a) a change in speed limit, or (b) a change in enforcement,

3. An accident modification factor associated with the change in speed, or the number of accidents or injured road users before and after the change in speed, at a specified level of severity, was stated,

4. The standard error of the accident modification factor, or the number of accidents or injured road users was stated or could be estimated based on data provided.

In earlier reviews (Elvik 2005, 2013A), studies of physical measures influencing speed, like speed humps or chicanes were also included. These studies have now been omitted, as it is not clear whether the effects found are attributable to changes in speed only or also to the physical changes made. If the intervention is a change in speed limit or enforcement, the physical layout of the road does not change. One can then be more confident that any changes in safety are mostly related to changes in speed.

Changes in speed limits provide the cleanest data about the relationship between speed and road safety, as usually nothing else changes very much. Changes in enforcement, particularly by means of speed cameras, also provides relatively unconfounded data. Speed cameras may be deployed on roads with a bad accident record. All studies of speed cameras included in this review have controlled both for long-term trends and regression-to-the-mean. Enforcement performed by police officers introduces some confounding, as police officers in practice will not enforce speed exclusively, but also other violations detected as a by-product of speed enforcement (not wearing seat belts, drinking and driving, etc.). This may affect not just speed, but other types of behaviour related to safety.

It was decided to focus on studies of the relationship between speed and fatalities and between speed and injury accidents. It is for these road safety outcomes the largest number of studies has been reported. In the meta-analysis, each estimate of

the relationship between change in speed and change in the number of accidents or injured road users was initially summarised as an estimate of the exponent in the Power model. This estimate is obtained as:

$$\text{Estimate of exponent} = \alpha = \frac{\ln\left(\dfrac{Y_1}{Y_0}\right)}{\ln\left(\dfrac{V_1}{V_0}\right)} \tag{8}$$

Where Y denotes accidents and V denotes speed. The individual estimates of α serve as the basis for an overall estimate for the exponent, obtained by inverse-variance meta-analysis or curve estimation for chained data points (see below). Each estimate of α is assigned a weight proportional to the inverse of the variance of the estimate. If it is assumed that there is no measurement error in mean speed, the denominator in equation 8 is a constant and the variance of α can be calculated by applying the relation $Var(kx) = k^2 Var(x)$. This assumption has been made as almost no studies report measurement error in speed. The variance of α is given by:

$$Var(\alpha) = \frac{\dfrac{1}{Y_0} + \dfrac{1}{Y_1}}{\left(\ln\left(\dfrac{V_1}{V_0}\right)\right)^2} \tag{9}$$

The statistical weight assigned to each estimate of power is $1/Var(\alpha)$. This is the statistical weight applied in fixed-effects meta-analysis. In fixed-effects meta-analysis it is assumed that variation around the weighted mean estimate is random only. To test whether this is correct, the following test statistic is computed:

$$Q = \sum_{i=1}^{g} W_i \cdot Y_i^2 - \frac{\left(\sum_{i=1}^{g} W_i \cdot Y_i\right)^2}{\sum_{i=1}^{g} W_i} \tag{10}$$

This is an estimate of variance. If it indicates that there is systematic variation between individual estimates of power, a random-effects meta-analysis is performed, and the statistical weights adjusted by adding a variance component τ^2. The statistical weight then becomes:

$$\text{Random effects statistical weight} = \frac{1}{Var(\alpha) + \tau^2} \tag{11}$$

The variance component (τ^2) is estimated as follows:

$$\text{Variance component } (\tau^2) = \frac{Q - (g-1)}{C} \tag{12}$$

In which Q is the estimate of variance given above (equation 10), g is the number of estimates and C is estimated as follows:

$$C = \sum_{g=1}^{n} W_i - \left(\frac{\sum_{g=1}^{n} w_i^2}{\sum_{g=1}^{n} w_i}\right) \tag{13}$$

Table 1 lists the studies that were included in the meta-analysis and some data for each study. The most common intervention was a change in speed limit. The mean speed of traffic nearly always changed in the same direction as the change of speed limit, i.e. declined when the speed limit was lowered and increased when the speed limit was raised. A reduction of the mean speed of traffic was nearly always associated with a reduction of the number of fatalities or injury accidents. Table 1 lists accident modification factors. An accident modification factor of 0.80 corresponds to an accident reduction of 20 %. The statistical weight of each accident modification factor is also listed. These weights vary considerably.

Table 1 about here

The studies listed in Table 1 have all been published after 2000 and are based on data fully or partly referring to years after 2000. Studies have been reported in Australia, Canada, Denmark, France, Great Britain, Hungary, Israel, Italy, New Zealand, Norway, Sweden, Turkey, and the United States. Initial and final speeds cover a large range from more than 120 km/h to less than 50 km/h. A total of 31 estimates of power for injury accidents and 18 estimates for fatalities were extracted from the studies.

Table 2 lists studies that were not included and explains for each study why it was not included. The most common reason for not including a study is that it does not report all data needed for inclusion, i.e. only reports accident data or speed data, but not both types of data. For one study (Høye 2015A) speed data were given for some of the study sites, but not all. Results based on the sites with both speed data and accident data were included (as a summary estimate for all these sites); the other results were omitted.

Table 2 about here

4 EXPLORATORY META-ANALYSIS

Before conducting a meta-analysis, it is useful to perform an exploratory analysis to assess the distribution of the estimates serving as input in the meta-analysis and the potential presence of bias, particularly publication bias. Publication bias is bias against publishing findings that are regarded as difficult to interpret or explain, like

finding that lower speed is associated with an increase in the number and severity of accidents.

A useful tool for exploratory meta-analysis is the funnel plot (Sterne and Egger 2001). It shows estimates on the abscissa and a measure of their precision, usually the standard error, on the ordinate. If the distribution of data points resembles a funnel turned upside down, with the narrow end at the top, and distribute symmetrically and unimodally around the weighted mean estimate, a meta-analysis makes sense. Figure 1 shows a funnel plot of estimates of the exponent of the Power model for fatalities.

Figure 1 about here

One extreme estimate of 154.582 was omitted from the figure to improve its readability. Standard error is plotted on a log scale with the smallest standard errors on top. The standard error of each data points is $1/\sqrt{weight}$. The data points are very widely and asymmetrically dispersed with a tail of high estimates to the right in the figure. The tail to the right may indicate publication bias. The trim-and-fill technique (Duval and Tweedie 2000A, 2000B, Duval 2005) was applied to assess the potential presence of publication bias. This technique trims away data points until those that remain are symmetrically distributed around the trimmed mean (which leaves out the data points that have been trimmed away).

Seven data points were trimmed away in Figure 1 (only six of these are shown). This reduced the value of the statistical weights by 2.6 %. The fixed-effects summary estimate of power was reduced from 4.417 to 4.333, a reduction of 1.9 %. The summary estimate of power is consistent with the value proposed by Nilsson (2004) for fatalities, which should be greater than 4 but smaller than 8, but likely to be much

closer to 4 than to 8 (see equation 2). The main analysis comparing the Power model and the Exponential model was based on all data points, but an analysis based only on the trimmed data points was performed as a sensitivity analysis.

Figure 2 shows a funnel plot of estimates of power for injury accidents. The shape of the plot resembles that for fatalities. Trim-and-fill trims away ten data points; however, these only represent 2.7 % of the statistical weights and thus count for little. The summary estimate of power changes from 2.374 to 2.168.

Figure 2 about here

The trimmed distribution of data points somewhat resembles a funnel.

5 FUNCTIONAL RELATIONSHIPS – AGGREGATE LEVEL

In order to compare the Power model and the Exponential model, data were sorted according to initial speed. As in the paper by Elvik (2013A), initial speed was sorted into groups of 10 km/h. For fatalities the highest group was initial speed between 120 and 129.9 km/h. There was one estimate of power based on this initial speed. Table 3 lists the number of estimates in each group for initial speed. There are 18 estimates in total.

Table 3 about here

Final speed is in many cases close to initial speed. The reason for this is that the changes from a given initial speed are often both increases and decreases that cancel each other when the average is computed. The exponents listed in Table 3 were estimated by relying on initial speed, which in some cases is an average of several

initial speeds in the same 10 km/h band. The exponents are weighted mean values, based on the statistical weights of each estimate.

Consistent with Elvik (2013A) a midpoint speed in each interval has been stipulated (125, 115, etc.). The exponents have been made to refer to equal-sized changes in speed, stated in km/h by making each of them refer to a change from the stipulated initial speed in a given interval to the stipulated initial speed in the interval below. All these changes are by 10 km/h.

Table 4 shows how the exponents have been applied in order to produce relative numbers of fatalities for all initial speeds from 125 to 55 km/h. Thus, for a change from 95 to 85 km/h, the accident modification factor (AMF), using the exponents listed in Table 3 is:

$$AMF_{85}^{95} = \left(\frac{85}{95}\right)^{3.763} = 0.658$$

This corresponds to an expected reduction of fatalities of 34.2 %. The initial number of fatalities at the highest initial speed is set equal to 100, so that the expected numbers at lower speeds can be interpreted as percentage changes. Reducing speed from 125 to 115 km/h is estimated to reduce the number of fatalities from 100 to 57.7. The next reduction in speed, from 115 to 105 km/h is estimated to reduce the number of fatalities further to 12.9.

Table 4 about here

It is seen from Table 4 that reducing speed from 125 to 95 km/h is estimated to almost eliminate fatalities, which is not plausible. When estimating coefficients for

the Power model and the Exponential model, analyses have therefore been performed both for all initial speeds and for initial speeds of 95 km/h or less.

Data sets similar to those shown in Tables 3 and 4 were developed for injury accidents. There were 30 data points in total for injury accidents. The statistical weight of each data point was, in general, larger than the statistical weights for fatalities. Table 5 shows estimated coefficients for the Power model and the Exponential model and the share of variance explained by of each of these models.

Table 5 about here

The upper half of Table 5 contains results for fatalities. Both the Power model and the Exponential model fit the data extremely well. The exponent of the Power model has a value of 6.7 to 5.5. These values are reasonable and are consistent with the values proposed by Nilsson (2004). The values are a little higher than the mean values obtained in the exploratory meta-analysis (4.4). However, the exponents in Table 5 are consistent with a random-effects mean estimate (5.417). A weighted curve estimation is identical to a least-squares meta-regression fitted to heterogeneous values of the exponent of the Power model.

The coefficient for speed in the Exponential model has a value of slightly more than 0.08. This value is also consistent with previous research. Elvik (2013A) found a value of 0.069 for fatal accidents. The value of the coefficient for fatalities ought to be slightly larger, since there is more than one fatality in each fatal accident and changes in speed influence not only the number of fatal accidents but also the number of fatalities in each fatal accident.

It should be noted that nearly all the high estimates of power that were trimmed away in the trim-and-fill analysis were associated with the highest initial speeds. This is evident also in Table 3, in which the mean values of the exponents are 16.4 in the 110-119.9 range for initial speed, and 10.1 in the 100-109.9 range for initial speed. Thus, the results for initial speeds of 95 km/h or less represent a sensitivity analysis omitting the highest exponents and are conservative estimates.

For injury accidents, the exponent of the Power model is estimated to roughly 4, and the speed coefficient in the Exponential model to slightly more than 0.06. These values are both larger than earlier research has found. Elvik (2013A) reported an exponent of about 2.1 and a coefficient of 0.034. The values found in this study are nearly the double of these values. Again, the values based on initial speeds of 95 km/h or less are the most robust and omit most of the data points deleted in the trim-and-fill analysis. Figure 3 illustrates the relationship, based on initial speeds of 95 km/h or less.

Figure 3 about here

The typical difference between the power function and the exponential function is apparent in Figure 3. The exponential function has a sharper curvature than the power function; it is steeper at high speeds and flatter at low speeds than the power function.

6 FUNCTIONAL RELATIONSHIPS – INDIVIDUAL LEVEL

In their review, Aarts and van Schagen (2006) discuss the results of studies of the relationship between a driver's speed and his or her accident involvement. They quote five studies. Three of them are based on self-reports. Two (Kloeden et al. 1997, 2001) are case-control studies made at accident sites. In discussing the studies, Aarts and Van Schagen conclude that: "For now, the results of Kloeden et al. best describe the relationship between individual vehicle speed and crash rate." Three case-control studies were made in Australia. The studies by Kloeden et al. (1997, 2001) were preceded by a pilot study by Moore et al. (1995), not quoted by Aarts and van Schagen (2006).

Hauer (2004) has criticised the Australian case-control studies. He notes that the studies did not control for driver characteristics. He further notes that stating relative risk as an odds ratio between the odds of accident involvement at a given speed and the odds of accident involvement at a reference speed may inflate estimates of risk and partly be a statistical artefact. These points are valid.

The data for the three Australian case-control studies are shown in Table 6. It is clear that these data can be analysed in many ways. Doing it the way Kloeden et al. (1997) did is just one possibility.

Table 6 about here

In this paper, the three studies have been re-analysed using the probability of accident involvement as the dependent variable and speed as the independent variable. Using Kloeden et al. (1997) as an example, the probability of accident involvement at the lowest speed is $=0/4 = 0.00$. At a speed of 60 km/h, it is 29/234 $= 0.12$. Curves were fitted to the probabilities by means of a power function and an

exponential function in order to compare these functions, and in order to compare the values of the coefficients to those found at the aggregate level. Three models were fitted:

1. Curves fitted to data points without weighting

2. Curves fitted to data points using the sum of cases and controls as statistical weight

3. Curves fitted to data points using the number of cases as statistical weight.

In general, the third type of model performed best. Table 7 presents the results of the analysis.

Table 7 about here

Both the Power model and the Exponential model fit the data well, but the Exponential model fits best. Estimated coefficients have values that are not very different from those found in studies of the relationship between the mean speed of traffic and road safety; if anything values are slightly lower than those found at the aggregate level of analysis. Thus, the relationship between speed and accident involvement at the individual level has the same shape, but is perhaps slightly weaker, as the relationship between speed and the number of accidents at the aggregate level. There is a high degree of consistency between the individual level and the aggregate level in the shape and strength of this relationship.

7 DISCUSSION

Speed remains an important risk factor both for accident occurrence and for injury severity. It even seems to have become more important after the year 2000 than before. There is no tendency for the relationship between speed and road safety to become weaker. One may, however, imagine that new safety systems on cars can make road safety outcomes more sensitive to changes in speed. Before cars had, for example, electronic stability control and emergency brake assistance, they may have been unable to avoid an accident both at 55 and 50 km/h, meaning that this difference in speed would not necessarily be associated with a difference in the number of accidents.

However, with these systems, a driver might just be able to make a rapid evasive manoeuvre and/or brake hard enough to avoid the accident or reduce its severity at 50 km/h but not at 55 km/h. Estimates for Norway (Elvik and Høye 2018) show that the share of car kilometres driven with electronic stability control increased from 1 % in 1996 to 86 % in 2018. The share of kilometres driven by cars with emergency brake assistance increased from 0 % in 1996 to 79 % in 2018.

For initial speeds around 55 km/h, Mountain et al. (2004, 2005) found exponents of the Power model in the range of 1.4 to 1.5. In an Australian study in 2007 (Kloeden et al. 2007), the exponent was about 6.5. In a recent study by Islam et al. (2015), the exponent was estimated to 10.3. While one should be careful not to read too much into these few data points, the trend is consistent with the argument made above, that automotive safety systems designed to avoid accidents will make the relationship to speed stronger than before, not weaker.

The main weakness of the study presented in this paper was that there were few studies, only 18 for fatalities and 31 for injury accidents. Previous reviews (Elvik 2005, 2013A) have been based on several hundred estimates, at least for injury accidents. However, it was decided to give priority to recent studies to assess whether the relationship between speed and road safety remains as strong as it was before 2000.

8 CONCLUSIONS

The main conclusions of the research presented in this paper can be summarised as follows:

1. There is a strong relationship between the mean speed of traffic and road safety, stated as the number of fatalities and the number if injury accidents.

2. Two mathematical models of the relationship, the Power model and the Exponential model, both describe the relationship with great precision.

3. The relationship between speed and road safety is not weaker in studies published after 2000 than in older studies.

4. The best current estimates of the exponent of the Power model are 5.5 for fatalities and 3.9 for injury accidents.

5. The best current estimates of the speed coefficient in the Exponential model are 0.08 for fatalities and 0.06 for injury accidents.

6. The relationship between a driver's speed and his or her involvement in accidents has the same shape as the relationship between the speed of traffic and road safety.

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REFERENCES

Aarts, L., van Schagen, I. 2006. Driving speed and the risk of road crashes: a review. Accident Analysis and Prevention, 38, 215-224.

Bobevski, I., Hosking, S., Oxley, P., Cameron, M. 2007. Generalised linear modelling of crashes and injury severity in the context of the speed-related initiatives in Victoria during 2000-2002. Report 268. Monash University Accident Research Centre, Melbourne, Australia.

Brijs, T., Wets, G., Krimpenfort, R., Offermans, C. 2006. Impact of hourly measured speed on accident risk in the Netherlands. Transportation Research Record, 1972, 85-93.

Cetin, V. R., Yilmaz, H. H., Erkan, V. 2018. The impact of increasing speed limit in Turkey: The case of Ankara-Sivrihisar road section. Case Studies in Transport Policy, 6, 72-80.

Cheng, Z., Lu, J., Li, Y. 2018. Freeway crash risk evaluation by variable speed limit strategy using real-world traffic flow data. Accident Analysis and Prevention, 119, 176-187.

Christensen, P., Ragnøy, A. 2007. Endring av fartsgrense fra 90 km/t til 80 km/t. Effekt på ulykker. Arbeidsdokument SM/1866/2007. Transportøkonomisk institutt, Oslo.

Cunningham, C. M., Hummer, J. E., Moon, J-P. 2005. An evaluation of the safety effects of speed enforcement cameras in Charlotte, North Carolina. Final Report. Institute for Transportation Research and Education, North Carolina State University, Raleigh, North Carolina.

Davis, R. M., Pless, B. 2001. BMJ bans "accidents". Accidents are not unpredictable. Editorial, British Medical Journal, 322, 1320-1321.

D'Elia, A., Newstead, S., Cameron, M. 2007. Overall impact during 2001-2004 of Victorian speed-related package. Report 267. Monash University Accident Research Centre, Melbourne, Australia.

De Pauw, E., Daniels, S., Franckx, L., Mayeres, I. 2018. Safety effects of dynamic speed limits on motorways. Accident Analysis and Prevention, 114, 83-89.

Duval, S. 2005. The trim and fill method. In Rothstein, H., Sutton, A. J., Borenstein, M. (Eds): Publication Bias in Meta-analysis: Prevention, assessment and adjustments, 127-144. Chichester, John Wiley and Sons.

Duval, S., Tweedie, R. 2000A. Trim and fill: a simple funnel plot based method of testing and adjusting for publication bias in meta-analysis. Journal of the American Statistical Association, 95, 89-98.

Duval, S., Tweedie, R. 2000B. A non-parametric trim and fill method of assessing publication bias in meta-analysis. Biometrics, 56, 455-463.

Elvik, R. 2005. Speed and road safety. Synthesis of evidence from evaluation studies. Transportation Research Record, 1908, 59-69.

Elvik, R. 2013A. A re-parameterisation of the Power Model of the relationship between the speed of traffic and the number of accidents and accident victims. Accident Analysis and Prevention, 50, 854-860.

Elvik, R. 2013B. A before-after study of the effects on safety of environmental speed limits in the city of Oslo, Norway. Safety Science, 55, 10-16.

Elvik, R., Christensen, P., Amundsen, A. H. 2004. Speed and road accidents. An evaluation of the Power Model. Report 740. Institute of Transport Economics, Oslo.

Gains, A., Nordstrom, M., Heydecker, B., Shrewsbury, J., Mountain, L., Maher, M. 2005. The national safety camera programme. Four-year evaluation report. December 2005. University College London and PA Consulting Group, London.

Gayah, V. V., Donnell, E. T., Yu, Z., Li, L. 2018. Safety and operational impacts of setting speed limit below engineering recommendations. Accident Analysis and Prevention, 121, 43-52.

Hauer, E. 2004. Speed and crash risk: an opinion. Report 04/02. Public Policy Department, Royal Automobile Club of Victoria, Melbourne.

Hauer, E., Bonneson, J. 2006. An empirical examination of the relationship between speed and road accidents based on data by Elvik, Christensen and Amundsen. Unpublished manuscript dated March 5, 2006. Prepared for the Highway Safety Manual Task Force.

Hosking, S., Newstead, S., Hoareau, E., Delaney, A. 2005. An evaluation of the 50 km/h default speed limit in regional Queensland. Report 265. Monash University Accident Research Centre, Melbourne.

Høye, A. 2014. Speed cameras, section control, and kangaroo jumps – a meta-analysis. Accident Analysis and Prevention, 73, 200-208.

Høye, A. 2015A. Safety effects of section control – an empirical Bayes evaluation. Accident Analysis and Prevention, 74, 169-178.

Høye, A. 2015B. Safety effects of fixed speed cameras – an empirical Bayes evaluation. Accident Analysis and Prevention, 82, 263-269.

Høye, A. 2017. Bilalder og risiko. Rapport 1607. Oslo, Transportøkonomisk institutt.

Imprialou, M-I. M., Quddus, M., Pitfield, D. E., Lord, D. 2016. Revisiting crash-speed relationships: A new perspective in crash modelling. Accident Analysis and Prevention, 86, 173-185.

Imprialou, M-I. M., Quddus, M., Pitfield, D. E. 2016. Predicting the impact of a speed limit increase using conditional-based multivariate Poisson lognormal regression. Transportation Planning and Technology, 39, 3-23.

International Transport Form (ITF). 2018. Speed and crash risk. OECD/ITF, Paris.

Islam, M. T., El-Basyouny, K., Ibrahim, S. E. 2014. The impact of lowered residential speed limits on vehicle speed behavior. Safety Science, 62, 483-494.

Islam, M. T., El-Basyouny, K. 2015. Full Bayesian evaluation of the safety effects of reducing the posted speed limit in urban residential area. Accident Analysis and Prevention, 80, 18-25.

Kloeden, C. N., McLean, A. J., Moore, V. M., Ponte, G. 1997. Travelling speed and the risk of crash involvement. Volume 1 – findings. NHMRC Road Accident Research Unit, University of Adelaide, Adelaide.

Kloeden, C. N., Ponte, G., McLean, A. J. 2001. Travelling speed and the risk of crash involvement on rural roads. Report CR 204. Road Accident Research Unit, Adelaide University, Adelaide.

Kloeden, C., Wooley, J., McLaen, J. 2007. A follow-up evaluation of the 50 km/h default urban speed limit in South Australia. Proceedings of Australasian road safety research, policing and education conference, Melbourne, 2007.

Kockelman, K. M. 2006. Safety impacts and other implications of raised speed limits on high-speed roads. Final report. NCHRP Web-only Document 90 (Project 17-23): Contractor's Final Report. Transportation Research Board, Washington D. C.

Li, R., El-Basyouny, K., Kim, A. 2015. Before-and-after empirical Bayes evaluation of automated mobile speed enforcement on urban arterial roads. Transportation Research Record, 2516, 44-52.

Li, H., Graham, D. J. 2016. Heterogeneous treatment effects of speed cameras on road safety. Accident Analysis and Prevention, 97, 153-161.

Lindenmann, H. P. 2005. The effects on road safety of 30 kilometer-per-hour zone signposting in residential districts. ITE-Journal, June 2005, 50-54.

Long, A. D., Kloeden, C. N., Hutchinson, T. P., McLean, A. J. 2006. Reduction of speed limit from 110 km/h to 100 km/h on certain roads in South Australia: a

preliminary evaluation. CASR Report 024. Centre for Automotive Research, The University of Adelaide, Australia.

Luoma, J., Rajamäki, R., Malmivuo, M. 2012. Effects of reduced threshold of automated speed enforcement on speed and safety. Transportation Research Part F, 15, 243-248.

Moore, V. M., Dolinis, J., Woodward, A. J. 1995. Vehicle speed and risk of a severe crash. Epidemiology, 6, 258-262.

Mountain, L. J., Hirst, W. M., Maher, M. J. 2004. Costing lives or saving lives? A detailed evaluation of the impact of speed cameras on safety. Traffic Engineering and Control, 45, 280-287.

Mountain, L. J., Hirst, W. M., Maher, M. J. 2005. Are speed enforcement cameras more effective than other speed management measures? The impact of speed management schemes on 30 mph roads. Accident Analysis and Prevention, 37, 742-754.

Nilsson, G. 2004. Traffic safety dimensions and the Power Model to describe the effect of speed on safety. Bulletin 221. Lund Institute of Technology, Department of Technology and Society, Traffic Engineering, Lund.

Povey, L. J., Frith, W. J., Keall, M. D. 2003. An investigation of the relationship between speed enforcement, vehicle speeds and injury crashes in New Zealand. Proceedings of the Road Safety Research, Policing and Education Conference, Sydney, Australia.

Ragnøy A. 2004. Endring av fartsgrenser. Effekt på kjørefart og ulykker. TØI rapport 729. Transportøkonomisk institutt, Oslo.

Sayed, T., Sacchi, E. 2016. Evaluating the safety impact of increased speed limits on rural highways in British Columbia. Accident Analysis and Prevention, 95, 172-177.

Shin, K., Washington, S., van Schalkwyk, I. 2009. Evaluation of the Scottsdale Loop 101 automated speed enforcement demonstration program. Accident Analysis and Prevention, 41, 393-403.

Sterne, J. A., Egger, M. 2001. Funnel plots for detecting bias in meta-analysis: Guidelines on choice of axis. Journal of Clinical Epidemiology, 54, 1046-1055.

Vadeby, A., Forsman, Å. 2018. Traffic safety effects of new speed limits in Sweden. Accident Analysis and Prevention, 114, 34-39.

Wang, X., Zhou, Q., Quddus, M., Fan, T., Fang, S. 2018. Speed, speed variation and crash relationships for urban arterials. Accident Analysis and Prevention, 113, 236-243.

Webster, D. C., Layfield, R. E. 2003. Review of 20 mph zones in London boroughs. Published project report PPR243. Transport Research Laboratory, Crowthorne.

Wilmots, B., Hermans, E., Brijs, T., Wets, G. 2017. Evaluating speed enforcement field set-ups by regional police in Belgium: An analysis of speed outcome indicators. Safety, 3. (doi:10.3390/safety3010001).

Yu, R., Quddus, M., Wang, X., Yang, K. 2018. Impact of data aggregation approaches on the relationship between operating speed and traffic safety. Accident Analysis and Prevention, 120, 304-310.

LIST OF FIGURES AND TABLES

Figure 1:

Funnel plot of estimates of power for fatalities

One estimate of 154.582 with a standard error of 857.905 not shown in diagram

Data points inside ellipse, plus one not shown, were trimmed away in trim-and-fill

Weighted mean estimate (4.417)

Fixed-effects standard error of estimate

Estimate of power

Funnel plot of estimates of power for injury accidents

Data points in the circle were trimmed away in trim-and-fill

One estimate of -143.174 with a standard error of 80.769 not shown in diagram

Weighted mean estimate (2.374)

Fixed-effects standard error of estimate

Estimate of power

Figure 3:

Relationship between speed and injury accidents

$y = 0.3776e^{0.0619x}$
$R^2 = 0.9181$

Power function = solid line
Exponential function = dashed line

$y = 3E\text{-}06x^{3.8601}$
$R^2 = 0.9726$

Y-axis: **Relative number of accidents (100 for the highest initial speed)**

X-axis: **Initial speed (km/h)**

Table 1:

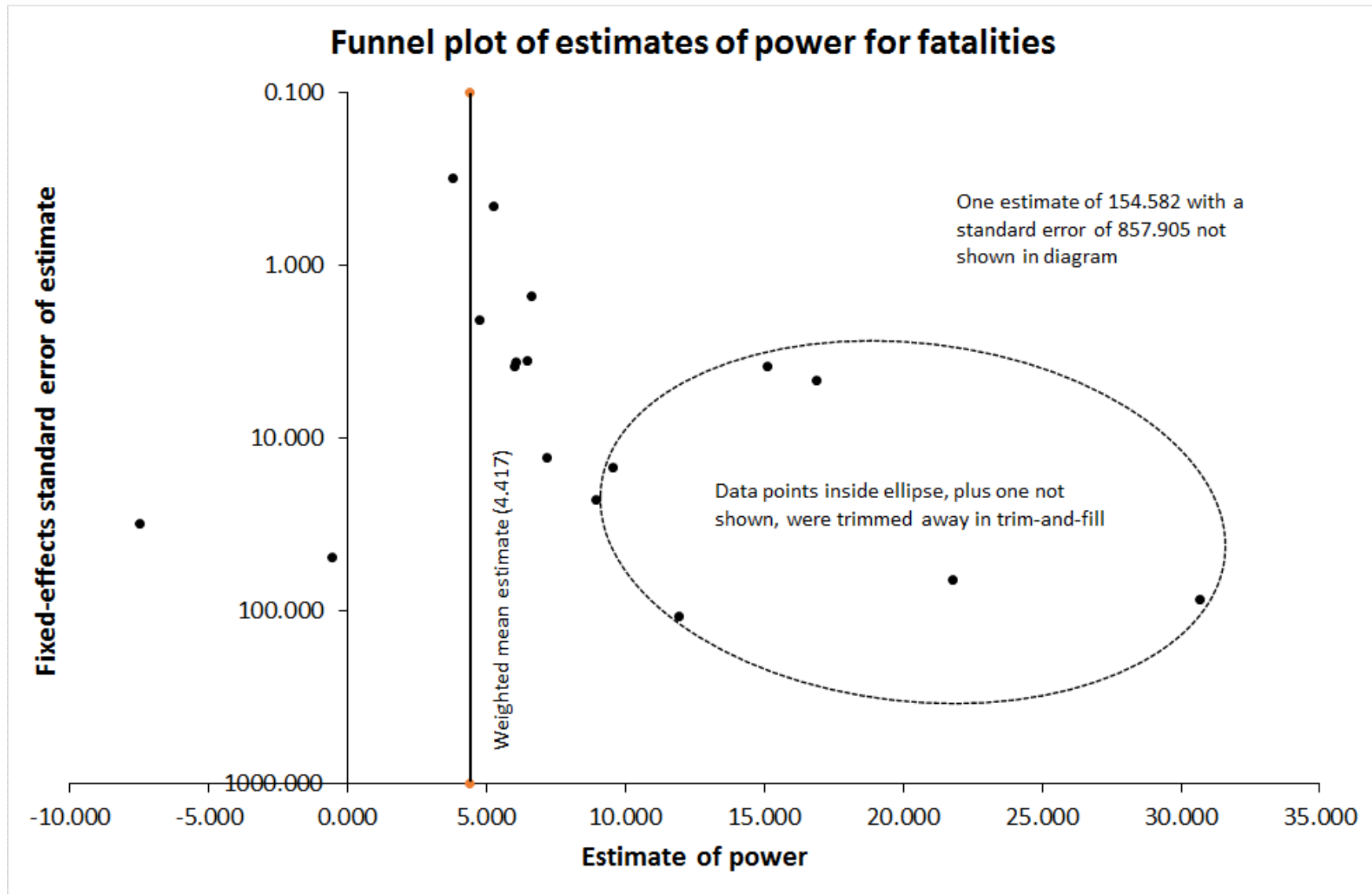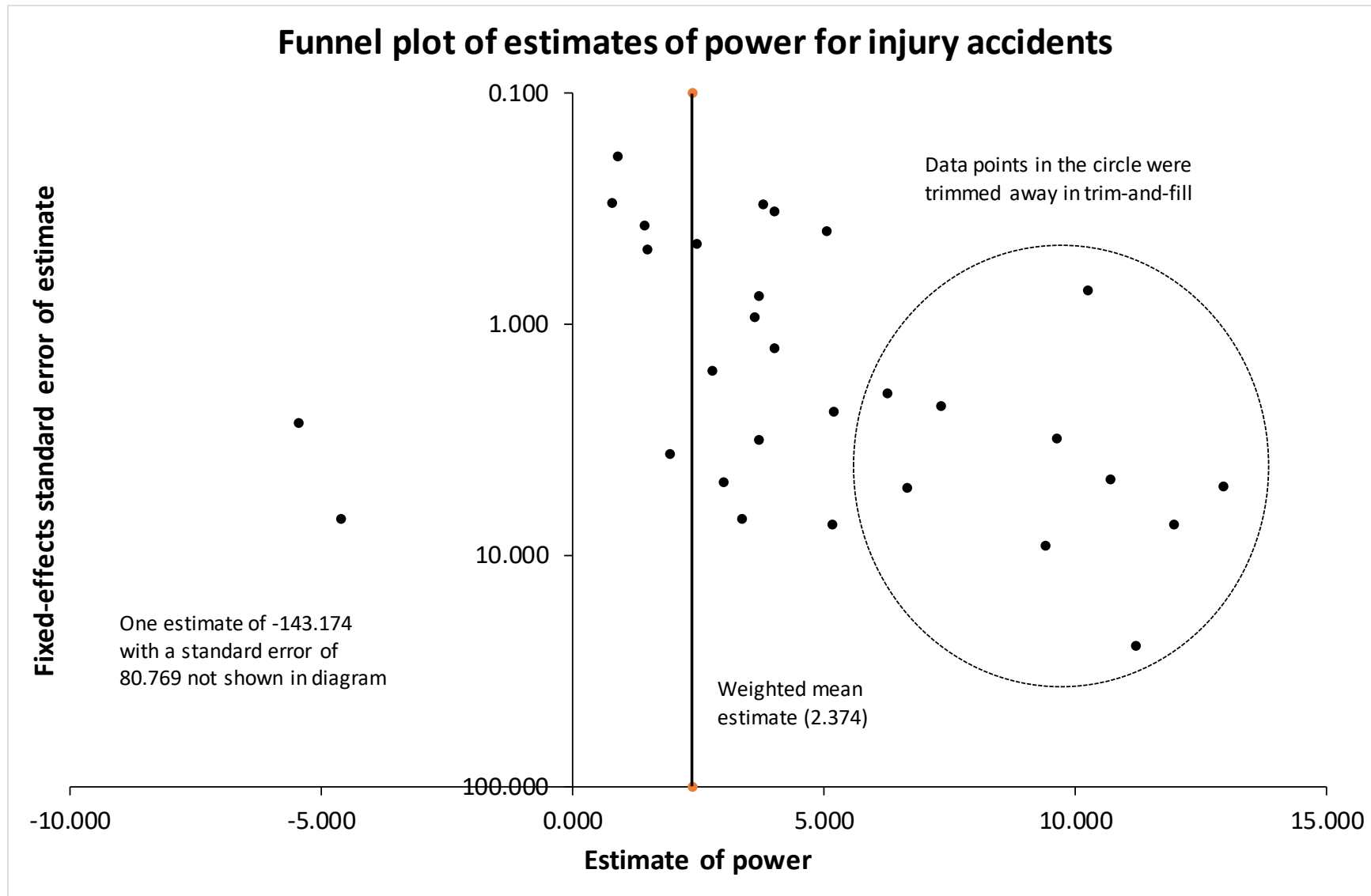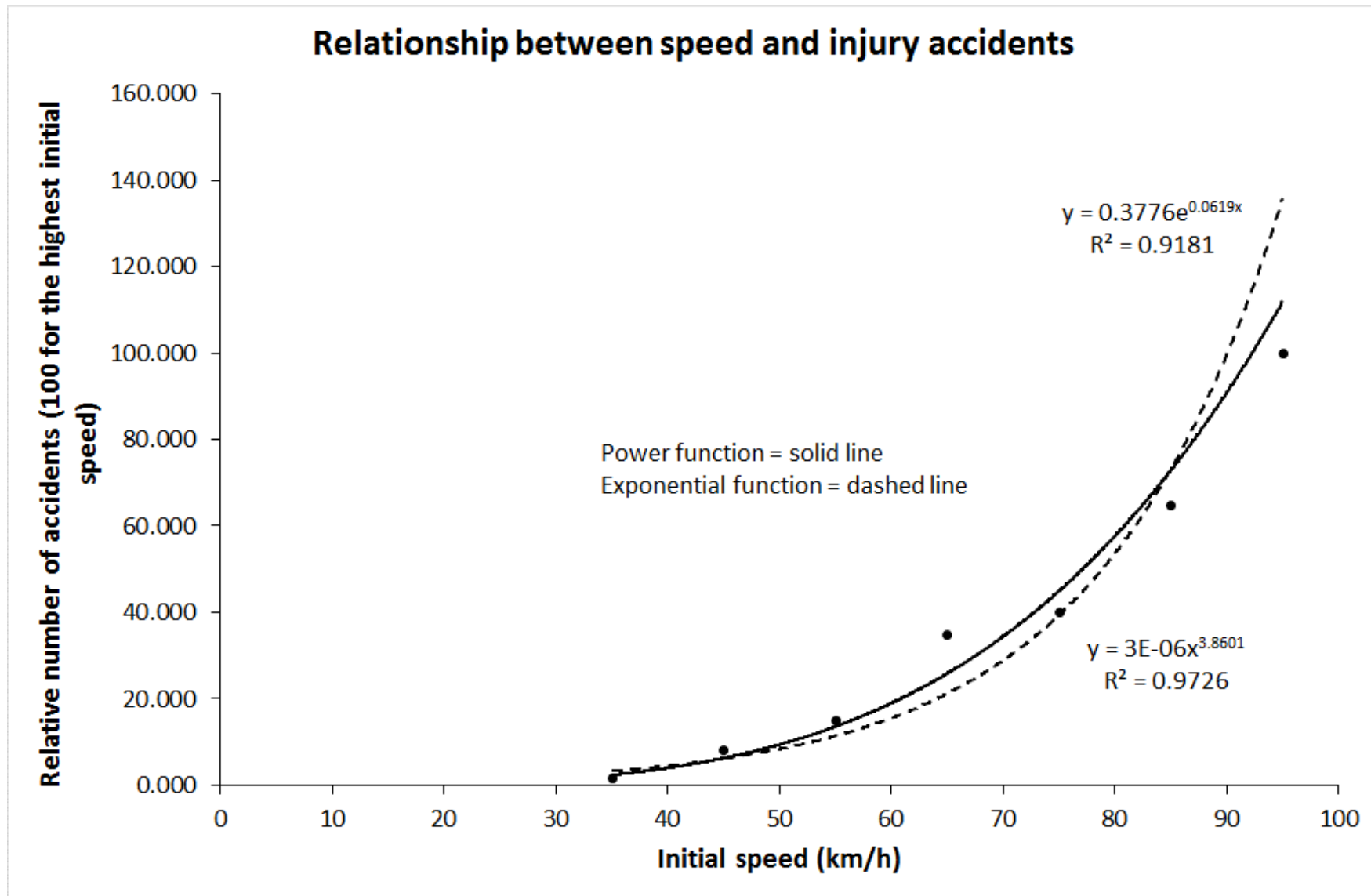| Study	Country	Intervention	Extent of intervention	Speed limit before (km/h)	Speed limit after (km/h)	Mean speed before (km/h)	Mean speed after (km/h)	Accident modification factor (fixed-effects weight)	Dependent variable
Mountain et al. 2004	Great Britain	Speed cameras	62 sites			52.8	45.7	0.810 (4.50786)	Injury accidents
Povey et al. 2004	New Zealand	Enforcement	Nationwide			102.7	99.4	0.656 (0.04063)	Injury accidents
Ragnøy 2004	Norway	Speed limit change	741 km	80	70	75.3	71.2	0.713 (0.07787)	Fatalities
Ragnøy 2004	Norway	Speed limit change	741 km	80	70	75.3	71.2	0.817 (1.15909)	Injury accidents
Cunningham et al. 2005	United States	Speed cameras	14 sites			67.8	66.0	0.871 (0.01900)	Injury accidents
Cunningham et al. 2005	United States	Speed cameras	14 sites			68.8	67.9	0.863 (0.00170)	Injury accidents
Gains et al. 2005	Great Britain	Speed cameras	1952 sites			54.5	50.7	0.838 (5.01534)	Injury accidents
Hosking et al. 2005	Australia	Speed limit change	Statewide	60	50	47.4	45.8	0.807 (0.25912)	Injury accidents
Mountain et al. 2005	Great Britain	Speed cameras	79 sites			53.1	46.5	0.830 (7.23920)	Injury accidents
Long et al. 2006	Australia	Speed limit change	1060 km	110	100	99.4	97.5	0.842 (0.00198)	Fatalities
Long et al. 2006	Australia	Speed limit change	1060 km	110	100	99.4	97.5	0.794 (0.01880)	Injury accidents
Bobevski et al. 2007	Australia	Speed cameras	Statewide			71.7	68.7	0.968 (11.41203)	Injury accidents
Christensen 2007	Norway	Speed limit change	393 km	90	80	85.1	82.2	0.780 (0.00614)	Fatalities
Christensen 2007	Norway	Speed limit change	393 km	90	80	85.1	82.2	0.880 (0.10053)	Injury accidents
D'Elia et al. 2007	Australia	Speed cameras	Statewide			72.0	68.2	0.954 (28.46628)	Injury accidents
Kloeden et al. 2007	Australia	Speed limit change	Statewide	60	50	55.8	52.0	0.634 (0.07915)	Fatalities
Kloeden et al. 2007	Australia	Speed limit change	Statewide	60	50	55.8	52.0	0.767 (11.0990)	Injury accidents
Kloeden et al. 2007	Australia	Speed limit change	Statewide	60	50	60.0	57.9	0.808 (0.06809)	Fatalities
Kloeden et al. 2007	Australia	Speed limit change	Statewide	60	50	60.0	57.9	0.836 (6.55870)	Injury accidents
Shin et al. 2009	United States	Speed cameras	10.5 km			117.6	103.6	0.520 (0.17909)	Injury accidents

Table 1, continued:

Study	Country	Intervention	Extent of intervention	Speed limit before (km/h)	Speed limit after (km/h)	Mean speed before (km/h)	Mean speed after (km/h)	Accident modification factor (fixed-effects weight)	Dependent variable
Elvik 2013B	Norway	Speed limit change	7.4 km	80	60	76.7	70.2	0.783 (0.40009)	Injury accidents
Elvik 2013B	Norway	Speed limit change	15.6 km	80	60	76.3	69.9	0.705 (0.62292)	Injury accidents
Elvik 2013B	Norway	Speed limit change	4.7 km	80	60	76.0	72.9	0.641 (0.04656)	Injury accidents
Høye 2015A	Norway	Section control	37.4 km			82.0	75.7	0.788 (0.04329)	Injury accidents
Islam et al. 2014; 2015	Canada	Speed limit change	181 km	50	40	50.5	47.2	0.501 (1.98220)	Injury accidents
Cetin et al. 2018	Turkey	Speed limit change	114 km	100	110	102.0	105.3	1.354 (0.00462)	Fatalities
Cetin et al. 2018	Turkey	Speed limit change	114 km	100	110	102.0	105.3	1.358 (0.10506)	Injury accidents
Gayah et al. 2018	United States	Speed limit change	21.2 km	80	72	81.7	72.2	0.609 (9.55026)	Injury accidents
Gayah et al. 2018	United States	Speed limit change	4.8 km	83	67	93.2	87.1	1.449 (0.18585)	Injury accidents
Gayah et al. 2018	United States	Speed limit change	15.6 km	113	89	103.8	103.3	1.996 (0.00015)	Injury accidents
ITF 2018	Hungary	Speed limit change	Nationwide	80	90	78.0	80.1	1.134 (0.23486)	Fatalities
ITF 2018	Denmark	Speed limit change	631 km	110	130	118.1	121.4	1.200 (0.03882)	Injury accidents
ITF 2018	Denmark	Speed limit change	506 km	110	110	118.2	116.5	0.873 (0.01225)	Injury accidents
ITF 2018	Israel	Speed limit change	39.8 km	100	110	107.2	104.6	1.120 (0.02077)	Injury accidents
ITF 2018	Israel	Speed limit change	54.5 km	90	100	110.6	103.6	0.620 (0.19657)	Injury accidents
ITF 2018	Israel	Speed limit change	60.0 km	100	110	107.8	110.6	1.090 (0.02103)	Injury accidents
ITF 2018	Israel	Speed limit change	21.6 km	90	100	95.9	102.7	1.140 (0.07635)	Injury accidents

Table 1, continued:

Study	Country	Intervention	Extent of intervention	Speed limit before (km/h)	Speed limit after (km/h)	Mean speed before (km/h)	Mean speed after (km/h)	Accident modification factor (fixed-effects weight)	Dependent variable
ITF 2018	France	Speed cameras	Nationwide			126.0	119.0	0.686 (0.44673)	Fatalities
ITF 2018	France	Speed cameras	1661 fixed			88.0	81.0	0.649 (4.91399)	Fatalities
ITF 2018	France	Speed cameras	932 mobile			93.0	86.0	0.745 (10.26551)	Fatalities
ITF 2018	France	Speed cameras	In 2009			112.0	109.0	0.633 (0.04701)	Fatalities
ITF 2018	Italy	Section control	40.4 km			83.4	75.2	0.682 (1.77662)	Injury accidents
Vadeby, Forsman 2018	Sweden	Speed limit change	261 km	110	120	111.9	115.3	0.799 (0.00103)	Fatalities
Vadeby, Forsman 2018	Sweden	Speed limit change	1071 km	90	100	92.9	95.9	1.997 (0.00023)	Fatalities
Vadeby, Forsman 2018	Sweden	Speed limit change	2831 km	110	100	100.5	98.4	0.524 (0.00014)	Fatalities
Vadeby, Forsman 2018	Sweden	Speed limit change	2831 km	110	100	98.4	96.7	0.812 (0.00009)	Fatalities
Vadeby, Forsman 2018	Sweden	Speed limit change	1216 km	70	80	84.6	84.8	1.441 (0.00000)	Fatalities
Vadeby, Forsman 2018	Sweden	Speed limit change	12858 km	90	80	87.7	84.7	0.592 (0.06888)	Fatalities
Vadeby, Forsman 2018	Sweden	Speed limit change	1065 km	90	70	82.6	79.4	1.024 (0.00043)	Fatalities

Table 2:

Study	Country	Reason for exclusion
Webster and Layfield 2003	Great Britain	Deals with physical measures to reduce speed
Lindenmann 2005	Switzerland	Deals with physical measures to reduce speed
Brijs et al. 2006	Belgium	Results do not show changes in the mean speed of traffic
Kockelman 2006	United States	Not possible to estimate statistical weights associated with results
Luoma et al. 2012	Finland	Does not contain data on accidents or injuries
Høye 2014	Several countries	Is a meta-analysis, not a primary study
Høye 2015A	Norway	Sites for which speed data were available were included, other sites excluded
Høye 2015B	Norway	Does not contain data on speed
Imprialou et al. 2015A	Great Britain	No intervention influencing speed is included; cross-sectional data only
Imprialou et al. 2015B	Great Britain	Is a predictive study only, not an evaluation of an actual intervention
Li et al. 2015	Canada	Does not contain data on speed
Li and Graham 2016	Great Britain	Does not contain data on speed
Sayed and Sacchi 2016	Canada	Does not contain data on speed
Wilmots et al. 2017	Belgium	Does not contain data on accidents or injuries
Cheng et al. 2018	China	States only percentage change in speed, not actual initial and final speed
De Pauw et al. 2018	Belgium	Does not contain data on speed
Wang et al. 2018	China	No intervention influencing speed is included; cross-sectional data only
Yu et al. 2018	China	No intervention influencing speed is included; cross-sectional data only

Table 3:

Range for initial speed	Number of estimates in range	Mean initial speed (km/h)	Mean final speed (km/h)	Mean estimate of exponent (Power model)	Standard error of exponent
120.0-129.9	1	126.0	119.0	6.594	1.496
110.0-119.9	2	112.0	112.1	16.432	4.563
100.0-109.9	2	101.3	101.9	10.128	14.497
90.0-99.9	4	95.9	94.0	3.763	0.312
80.0-89.9	5	85.6	82.4	5.354	0.448
70.0-79.9	2	76.7	75.7	5.060	1.788
60.0-69.9	1	60.0	57.9	5.984	3.832
50.0-59.9	1	55.8	52.0	6.461	3.555

Table 4:

Initial speed (km/h)	Final speed (km/h)	Estimated AMF based on mean exponent	Relative number of fatalities	Statistical weight
125	115	0.577	100.00	0.447
115	105	0.224	57.71	0.048
105	95	0.363	12.94	0.005
95	85	0.658	4.70	10.268
85	75	0.512	3.09	4.989
75	65	0.485	1.58	0.313
65	55	0.358	0.77	0.079
55	45	0.273	0.28	0.068
45			0.08	2.027 #

Statistical weight set equal to mean value of weights for initial speeds between 125 and 55 km/h

Table 5:

Outcome severity	Statistical weighting	Data points included	Exponent of Power Model (standard error)	Share of explained variance (R-squared)	Coefficient of exponential model (standard error)	Share of explained variance (R-squared)
Fatalities	No	All	6.724 (0.458)	0.969	0.086 (0.004)	0.986
	Yes	All	5.762 (0.258)	0.968	0.083 (0.003)	0.978
	No	≤ 95 km/h	5.531 (0.208)	0.994	0.081 (0.008)	0.967
	Yes	≤ 95 km/h	5.493 (0.097)	0.995	0.081 (0.003)	0.978
Injury accidents	No	All	4.154 (0.235)	0.978	0.060 (0.005)	0.957
	Yes	All	3.977 (0.062)	0.976	0.067 (0.002)	0.926
	No	≤ 95 km/h	3.860 (0.290)	0.973	0.062 (0.008)	0.918
	Yes	≤ 95 km/h	3.951 (0.062)	0.976	0.067 (0.002)	0.923

Table 6:

Data for Moore et al. (1995)				Data for Kloeden et al. (1997)				Data for Kloeden et al. (2001)			
Speed (km/h)	Cases	Controls	Total	Speed (km/h)	Cases	Controls	Total	Speed (km/h)	Cases	Controls	Total
30	0	5	5	35	0	4	4	35	0	2	2
40	1	16	17	40	1	5	6	45	1	25	26
50	2	46	48	45	4	30	34	55	4	68	72
60	7	121	128	50	5	57	62	65	7	111	118
70	5	110	115	55	19	133	152	75	9	162	171
80	6	68	74	60	29	205	234	85	14	151	165
90	7	40	47	65	36	127	163	95	12	139	151
100	8	29	37	70	20	34	54	105	7	117	124
110	2	12	14	75	9	6	15	115	21	44	65
120	7	3	10	80	9	2	11	125	3	9	12
				85	8	1	9	155	5	2	7

Table 7:

Study	Weighting	Exponent of Power model (standard error)	P-value	Goodness-of-fit (R-squared)	Coefficient of exponential model (standard error)	P-value	Goodness-of-fit (R-squared)
Moore et al. 1995	No	2.006 (0.554)	0.008	0.652	0.029 (0.006)	0.002	0.758
	By no. of cases	2.958 (0.240)	0.000	0.779	0.039 (0.002)	0.000	0.866
Kloeden et al. 1997	No	2.942 (0.662)	0.002	0.712	0.052 (0.009)	0.001	0.790
	By no. of cases	4.278 (0.164)	0.000	0.831	0.069 (0.002)	0.000	0.885
Kloeden et al. 2001	No	2.109 (0.480)	0.002	0.707	0.026 (0.004)	0.000	0.806
	By no. of cases	2.663 (0.202)	0.000	0.681	0.030 (0.002)	0.000	0.754
All studies #	No	2.267 (0.318)			0.030 (0.003)		
	By no. of cases	3.487 (0.112)			0.046 (0.001)		

Coefficient estimates combined by inverse-variance technique