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A synthesis of studies of access point density as a risk factor for road accidents

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ABSTRACT

Studies of the relationship between access point density (number of access points, or driveways, per kilometre of road) and accident frequency or rate (number of accidents per unit of exposure) have consistently found that accident rate increases when access point density increases. This paper presents a formal synthesis of the findings of these studies. It was found that the addition of one access point per kilometre of road is associated with an increase of 4 % in the expected number of accidents, controlling for traffic volume. Although studies consistently indicate an increase in accident rate as access point density increases, the size of the increase varies substantially between studies. In addition to reviewing studies of access point density as a risk factor, the paper discusses some issues related to formally

synthesising regression coefficients by applying the inverse-variance method of meta-analysis.

Key words: access points; accident rate; accident prediction models; meta-analysis; regression coefficients

1 INTRODUCTION

It has been known for a long time that many access points, also known as driveways, along a road increases the risk of accidents. David Schoppert (1957) reported that accident rate (number of accidents per vehicle kilometre of travel) increased as the number of residential driveways per kilometre of road increased. Traffic engineers have understood for at least sixty years that to make a road safe, it cannot have direct accesses to abutting properties. Access free roads are known as freeways in the United States and motorways in Europe.

Although the fact that high access point density is associated with high accident risk has been known for a long time, the precise shape of the relationship is less known. For a long period, there was little research into the relationship, but following the introduction of accident prediction models suitable for analysing count data (Jovanis and Chang 1986), several studies have been made, particularly in the United States. In recent years, the number of papers dealing with access point density appears to be increasing (Cafiso et al. 2010, Brimley et al. 2012, Avelar et al. 2013, Huang et al. 2014, Alluri et al. 2015). The increasing interest in the topic raises the issue of whether studies reach consistent or discrepant findings. A tool for investigating this issue is meta-analysis. As far as is known, no meta-analysis has tried to summarise the findings of studies dealing with access point density as a risk factor for accidents.

The main objective of this paper is to synthesise the results of studies of the relationship between access point density and accident rate, applying inverse-variance meta-analysis. Such a synthesis will show the typical or "average" relationship between access point density and accident rate, as well as the variability of the relationship.

To obtain a synthesis of studies, it is necessary to perform a meta-analysis of regression coefficients. This raises methodological problems. A secondary objective of the paper is to discuss methodological problems in meta-analysis of regression coefficients.

2 LITERATURE SURVEY AND STUDY CODING

Relevant studies were identified by searching the Handbook of Road Safety Measures (Høye et al. 2017), Sciencedirect, Google Scholar and the Transportation Research Board online library. Search terms used were "driveways and safety", "access points and safety", "driveways and accidents" and "access points and accidents". A total of 27 studies were identified, of which 20 were included in the meta-analysis. Table 1 lists all studies and gives the reason why some studies were not included in the meta-analysis.

Table 1 about here

Studies were omitted from the meta-analysis for three main reasons: (1) The access point density variable was not defined the same way as in other studies; (2) The standard errors of regression coefficients were not reported; (3) The statistical model was of a different form than other studies, making the regression coefficients incomparable. As will be discussed in the next section, it is essential that all studies included in a meta-analysis define access point density the same way and apply models of the same mathematical form reporting both regression coefficients and their standard errors.

For each of the studies included in the meta-analysis, the following information was coded (in addition to bibliographic information for study identification):

1. Publication year
2. Country of origin
3. Type of accident prediction model
4. Accident severity
5. Type of accidents included
6. Coefficient for access point density as originally stated
7. Coefficient for access point density converted to metric scale (if needed)
8. Standard error of coefficient for access point density
9. Number of covariates included in accident prediction model
10. If a separate coefficient has been estimated for traffic volume
11. Number of accident prediction models fitted and reported

Table 2 shows information regarding most of these characteristics for the studies included in the meta-analysis. It is seen that quite many studies had to be re-analysed to be included in the meta-analysis. The reasons for this are explained below.

Table 2 about here

3 PROBLEMS OF FORMALLY SYNTHESISING REGRESSION COEFFICIENTS

Meta-analysis of regression coefficients fitted in multivariate models is only feasible if some conditions are fulfilled (Becker and Wu 2007, Card 2012). First, the dependent variable, Y, (in this study: accident rate) must be identically defined and measured in all studies. This is necessary because regression coefficients depend on scale. Second, the independent variable of principal interest, X, (in this study: access point density) must be identically defined and measured in all studies. The reason is again that if X has a different scale in different studies, the regression coefficients will not be comparable. Third, additional variables included in a model, Zs, (in this study, for example, number of lanes) included in the regression models should be the same in all studies. The last condition is almost never fulfilled. There are differences of opinion among analysts as to whether the third condition must be fulfilled.

Becker and Wu (2007) discuss a number of approaches that have been taken by meta-analysts, including a standard inverse-variance approach. Each regression coefficient is then assigned a statistical weight which is inversely proportional to its sampling variance. Sampling variance is estimated as the squared standard error of the coefficient. This approach is very often feasible, as almost any statistical software used in regression modelling will report the standard errors of the regression coefficients. It has been applied in a previous paper by Elvik and Bjørnskau (2017) and will be taken in this paper. Regression coefficients included in a meta-analysis must comparable in terms of:

1. Being estimated by means of models of the same mathematical form

2. Referring to an identically defined access point density variable
3. Stating the standard error of the coefficient

The studies listed in Table 2 differ with respect to their mathematical form. The dependent variable is either accident rate (number of accidents per million vehicle kilometres of travel) or the number of accidents. Studies using accident rate as dependent variable are either purely descriptive studies in which no model has been fitted to the data or linear regression models of the following form (see e.g. Mouskos et al., 1999A):

Accident rate = $\alpha + \beta_1 \cdot AADT + \beta_2 \cdot Access\ point\ density + \beta_n \cdot Z_n$ (1)

In equation 1, *a* is the constant term and the β_i-s are coefficients for the independent variables. Models of this form usually include traffic volume (AADT), access point density and one or more additional variables (Zs). It is seen that this type of model assumes a linear relationship between traffic volume and accident rate.

Models in which the number of accidents is dependent variable often have the following form (Lord and Mannering 2010):

Predicted number of accidents = $e^{\beta_0} L^{\beta_1} AADT^{\beta_2} e^{(\sum_n^{i=1} \beta_n X_n)}$ (2)

In equation 2 e denotes the exponential function, i.e. the base of the natural logarithms (2.71828) raised to the power of a regression coefficient β. The first term is the constant term. The next two terms refer to the length of road sections (L) and traffic volume (AADT). The final term ($e^{(\Sigma\beta nXn)}$) is a set of predictor variables (X) other than traffic volume, which may influence the number of accidents. Access point density would belong to this group. Please note that the following formulations are mathematically identical:

$$X^{\beta_1} = e^{(\beta_1 \cdot \ln(X))} \qquad (3)$$

The following reduced model is treated as being of the same mathematical form as the more complete model stated in equation 2:

$$\text{Predicted accident rate} = \alpha \cdot e^{(\beta \cdot X)} \qquad (4)$$

Equation 4 is an exponential function with only one independent variable, X, (access point density), fitted to data points showing accident rates for different access point densities. Traffic volume enters only in the form of an accident rate on the left side. Using a model like the one given in equation 4 is potentially misleading (Hauer 1995), as accident rate is neither independent of traffic volume nor a linear function of it. This raises the issue of whether it makes sense to combine the results of the two different types of models found in the literature, i.e. those using accident rate as dependent variable and those using the number of accidents as dependent variable. This issue has been decided by means of exploratory analysis, presented in section 5 of the paper. Before presenting the exploratory analysis, editing and re-analysis of studies to make them as comparable as possible will be presented.

4 EDITING AND RE-ANALYSING STUDIES FOR INCLUSION IN META-ANALYSIS

It was necessary to edit and re-analyse some of the studies for inclusion in the meta-analysis. The six old Norwegian studies, all published before 1980, were merged into a single study. The studies are listed in Table 3.

Table 3 about here

These studies were all simple bivariate descriptive studies of the relationship between access point density and accident rate. They rely on partly overlapping data sets and the results of them can therefore not be treated as statistically independent. The accident sample in some of the studies was very small, see Table 3. None of the studies provided a regression coefficient for access point density. The studies are therefore not comparable to more recent studies unless they are re-analysed to obtain a regression coefficient. To increase the precision of the re-analysis, the studies were combined using the number of accidents as statistical weight. Access point density was stated as intervals. A typical value, close to the midpoint of each interval was selected as representative. Midpoints were 3 for the 0-5 interval, 11 for the 6-15 interval, 23 for the 16-30 interval and 40 for the 30- interval. Weighted mean accident rates were computed by means of meta-regression (Lipsey and Wilson 2001), using Ln(accident rate) as dependent variable. Figure 1 shows the results.

Figure 1 about here

According to the model with the smallest residual term, the coefficient for access point density was 0.0356, with a standard error of 0.0073. The function resulting from this coefficient is shown in Figure 1.

The next Norwegian study, Muskaug (1985), was much more comprehensive than the first six. It included the whole network of national roads in Norway and was essentially a complete census of access point density and its relationship to accident rate. It employed the technique of analysis still common at that time, using accident rate as the dependent variable. An example of the results of the study is given in Table 4.

Table 4 about here

By examining Table 4, one can see that accident rate depends both on AADT and access point density. Accident rate is negatively related to AADT; the higher the AADT, the lower the accident rate. Conversely, the higher access point density, the higher the accident rate. To describe the variation in the accident rates given in Table 4, a model should therefore include both AADT and access point density.

The report by Muskaug (1985) lists all relevant data in an appendix. Thus, for each cell in Table 4, it is possible to estimate AADT by using data on road length and vehicle kilometres of travel. Furthermore, the number of accidents in each cell of Table 4 is also stated. Based on this information, a model was fitted to the accident rates in Table 4 by means of meta-regression (Lipsey and Wilson 2001). The number of accidents was used as a fixed-effects statistical weight. The dependent variable was Ln(accident rate). The following model had the smallest residual term:

Accident rate = $e^{(0.0993+(0.0233 \cdot Access\ point\ density)+(-0.2037 \cdot \ln(AADT))}$

The standard error for the coefficient for access point density was 0.0014. The coefficient for ln(AADT) is negative. This shows that accident rate is negatively related to AADT. The model fits the accident rates quite well and shows that one may use accident rate as dependent variable in a model while allowing it to be non-linear with respect to traffic volume. Figure 2 shows actual and fitted accident rates.

Figure 2 about here

Papayannoulis et al. (1999) present a number of Tables showing how accident rate varies according to access point density. The Tables are descriptive only and do not contain any regression coefficients. Table 1 in their paper was selected for fitting a curve to the data points. An exponential function with a coefficient of 0.016 for access point density (standard error 0.004) fitted the data very well. Eisele and Frawley (2005) presented data on access point density and accident rate in Table 3 of their paper. These data were punched and an exponential curve fitted to them by means of the curve fitting routine in SPSS. The coefficient for access point density has a value of 0.015, with a standard error of 0.005. The same procedure was used for Schultz et al. (2007), using Figure 5 of their paper as source. The coefficient for access point density was estimated to a value of 0.053, with a standard error of 0.019. Finally, Huang et al. (2014) examine a new definition of access point density, which reflects the impact of traffic speed variation. Their study was re-analysed applying a standard definition of access point density, i.e. not their new version of the concept. 28 data points found in Tables 7 and 8 of their paper were punched and a negative binomial regression model fitted to these data points. AADT was entered as a natural logarithm. The following model best fitted the data (standard errors of coefficients in parentheses):

Number of accidents =

$$e^{[-12.519\ (4.461)+(0.087\ (0.0188)\cdot Access\ points\ per\ mile)+(1.311\ (0.4155)\cdot \ln(AADT))]}$$

The regression coefficients for access point density either refer to access points per mile or access points per kilometres. All regression coefficients for access point density were converted to a metric scale. If the original coefficient referred to access points per mile, it was multiplied by 1.609. This conversion does not affect the estimate of risk. As an example, Vogt and Bared (1998) estimated the coefficient for injury accidents (Table 28 of their report) to the value of 0.0062. If there are two access points per mile, risk is $e^{(0.0062 \cdot 2)}$ = 1.0125. Two access points per mile corresponds to 1.243 per kilometre. Thus, after metric conversion, the estimate of risk is $e^{(0.00998 \cdot 1.243)}$ = 1.0125. Each regression coefficient was assigned an inverse-variance statistical weight, defined as:

$$\text{Statistical weight } (w_{\text{fixed}}) = \frac{1}{SE^2} \qquad (5)$$

SE is the standard error of the regression coefficient.

5 EXPLORATORY ANALYSIS

5.1 Meta-regression of variation in coefficient estimates

A total of 20 estimates of regression coefficients were available for analysis after the re-analyses described in section 4. Eight coefficients were based on models using accident rate as dependent variable and not allowing for non-linearity in the relationship between traffic volume and accident rate. Twelve coefficients were based on models using the number of accidents as dependent variable or accident rate allowing for non-linearity in the relationship between traffic volume and accident rate. Can coefficients for access point density based on these different types of models be formally synthesised? To answer this question, meta-regression was run (Lipsey and Wilson 2001). The meta-regression software fits four types of models to the data: (1) A fixed-effects model fitted by means of ordinary least squares regression; (2) A random-effects model fitted by the method of moments; (3) A maximum likelihood random-effects model; and (4) A restricted maximum likelihood random-effects model. The maximum likelihood models are fitted by an iteration routine that minimises the value of the residual variance component (see next section for definition of the variance component); i.e. the adjusted statistical weights assigned to each estimate are determined so as to minimise residual variance. The restricted maximum likelihood model fitted the data best. The coefficients estimated in this model are shown in Table 5. The dependent variable was the coefficient for access point density.

Table 5 about here

The coefficients for access point density varied between -0.016 and 0.140 after conversion to metric scale. The main objective of meta-regression was to determine whether there was a statistically significant difference between coefficients estimated in models using accident rate as dependent variable and models using the number of accidents (or a non-linear accident rate) as dependent variable. This is referred to as model type in Table 5. As can be seen, there was no statistically significant difference in the coefficients for access point density between the two types of models. The P-value of the meta-regression coefficient for model type is 0.2502. The other two variables included in the meta-regression – number of covariates controlled for and publication year – were also not significantly related to the value of the regression coefficients for access point density. Based on this analysis, it is concluded that the regression coefficients for access point density are sufficiently homogeneous for a formal synthesis of them to make sense.

5.2 Funnel plot analysis

The next stage of exploratory analysis was to prepare a funnel plot of the estimates of the regression coefficients for access point density. This plot is shown in Figure 3.

Figure 3 about here

Estimates are plotted on the abscissa; the standard error of each estimate is plotted on the ordinate. Please note that the scale for the ordinate is inverted, so that estimates with the smallest standard errors are on top of the diagram. The underlying idea is that the distribution of estimates should resemble a funnel turned upside down; i.e. a small spread at the top of the diagram and a large spread at the bottom. The data points are widely scattered in the diagram and do not clearly show the shape of a funnel turned upside down. A fixed-effects summary regression coefficient was estimated to help test for outlying data points and the possible presence of publication bias (Borenstein et al. 2009, Duval and Tweedie 2000A, 2000B, Duval 2005). To test for outlying data points, the summary regression coefficient is re-estimated N times, each time omitted one of the primary estimates. If the omission of a primary estimate is associated with a statistically significant change in the summary estimate based on N – 1 primary estimates, the omitted estimate is classified as outlying. Two regression coefficients were found to be outlying, as indicated by the dotted ellipse at the top of Figure 3. The outlying data points are located on both sides of the weighted mean regression coefficient and tend to counterbalance each other. They have been retained in the main analysis and the test for outlying data points was repeated when a random-effects model of meta-analysis was adopted.

A trim-and-fill analysis was applied to test for the possible presence of publication bias. The trim-and-fill method is based on the assumption that the data points in the funnel plot should have a symmetric distribution around the summary mean if there is no publication bias. Asymmetry indicates publication bias and the trimmed mean, estimating after data points have been trimmed away, indicates what the summary estimate of the regression coefficient would have been if there was no publication bias. Two estimators are commonly used: L and R.

To estimate these and test for publication bias, primary estimates of the regression coefficients are sorted from the lowest to the highest. A summary estimate of the regression coefficient is obtained and the differences between the individual estimates and the summary estimate are computed. These differences are then ranked from the smallest to the largest. Ranks are signed. Thus, any estimate of risk lower than the mean gets a negative rank. Any estimate higher than the mean gets a positive rank. The estimator R is based on the length of the rightmost number of ranks associated with positive effects, i.e. the number of positive ranks larger than the absolute value of any of the negative ranks. Denoting this length with γ, the estimator is defined by $R_0 = \gamma - 1$. The second estimator is based on the sum of ranks for the positive effects. Denoting the ranks by r_i, the sum of positive ranks is defined by $\boldsymbol{T_n} = \sum_{\boldsymbol{r_i}>0} \boldsymbol{r_i}$, an estimator of the number of missing studies is defined by:

$$L_0 = \frac{4T_n - n(n+1)}{2n-1} \qquad (6)$$

To give readers an understanding of a trim-and-fill analysis, it has been reproduced in Table 6. The first column lists the twenty estimates of the regression coefficient for access point density from lowest to highest value. The next two columns show the fixed-effects statistical weight of each coefficient and the product of the coefficient and the fixed-effects weight. The sum of products (26540.220) divided by the sum of weights (916359.867) gives the weighted summary coefficient (0.029). Differences between each coefficient and the summary coefficient are taken and ranked. The most negative rank is -16, and the four most positive are 17, 18, 19 and 20.

Table 6 about here

Therefore, by the definition given above, R is 3 (four higher ranks minus one). The value of L is (4 · 139-(20 · 21))/((2 · 20) – 1) = 3.49. The procedure is repeated until the ranks no longer change value.

The four data points that were trimmed away represent 2.9 % of the total statistical weights and change the summary estimate of the regression coefficient by 10 %. There is thus a weak indication of publication bias, but not of a magnitude that casts serious doubt on the main results of the study.

6 MAIN ANALYSIS

As noted above, a random-effects model was adopted in the main analysis. The fixed-effect statistical weight is then adjusted by adding a between-study variance component, τ^2, and becomes:

$$\text{Random effects statistical weight } (w_{random}) = \frac{1}{SE_i^2 + \tau^2} \quad (7)$$

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

$$\text{Variance component } (\tau^2) = \frac{Q-(g-1)}{C} \quad (8)$$

In which Q is a measure of variance, g is the number of estimates (here 20) and C and Q are defined as follows:

$$C = \sum_{g=1}^{n} w_i - \left(\frac{\sum_{g=1}^{n} w_i^2}{\sum_{g=1}^{n} w_i}\right) \quad (9)$$

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

The summary estimate of the regression coefficient was 0.0390. The standard error of the summary regression coefficient was 0.0029. The relationship between access point density and relative accident rate based on these values is shown in Figure 4.

Figure 4 about here

According to the best estimate, an access point density of 43 per kilometre (the maximum value in Figure 4) is associated with an increase in accident rate by a factor of about 5.3. The lower 95 % confidence limit is a factor of 4.2 and the upper 95 % confidence limit a factor of about 6.9. The two regression coefficients that were classified as outlying according to the fixed-effects model were not outlying according to the random-effects model.

7 SENSITIVITY ANALYSIS

The regression coefficients for access point density varied considerably. If the lowest one is used, relative accident rate at 43 access points per kilometre (if set to 1.0 at 0 access points per kilometre) is 1.35. If the highest coefficient is used, relative accident rate at 43 access points per kilometre of road becomes 411.22. It should be noted that the negative regression coefficient found by Ivan et al. (2000) referred to single-vehicle accidents. A positive regression coefficient was found for multi-vehicle accidents. The combined coefficient, applying to total accidents (the sum of single and multi) was positive.

A regression coefficient for a given variable is normally influenced by which other variables are included in a model. Omitted variables is always a concern in regression models dealing with road safety. The number of accidents is influenced by very many variables and it is impossible to include all of them in any regression model. Is the value of the regression coefficient influenced by how many covariates a model includes? Figure 5 sheds light on this question.

Figure 5 about here

The regression models included in the meta-analysis included up to 12 covariates. Figure 5 shows that there is no relationship between the number of covariates included in a model and the estimated value of the regression coefficient for access point density. It is thus unlikely that the positive regression coefficients found for access point density are merely the result of poor control for other factors influencing accident rate.

The studies included span a considerable period of time. The oldest study was reported in 1968 and was based on data that are now more than fifty years old. The most recent study was reported in 2014. Are the results stable over time, or is there a tendency for the regression coefficient for access point density to change value over time? Figure 6 investigates this question.

Figure 6 about here

There is no statistically significant relationship between publication year and the estimated value of the regression coefficient for access point density. A weak positive tendency is found, suggesting that the relationship between access point density and accident rate has not become weaker over time.

8 DISCUSSION

It is increasingly common to describe the association between a risk factor and accident occurrence by means of a continuous function, developed by means of multivariate statistical models. For some risk factors, for example the relationship between blood alcohol concentration and the rate of accident involvement, this approach goes far back in time, with the first functions being fitted to data in the 1960s (Borkenstein et al. 1964). Functions have also been used for a long time to describe the relationship between access point density and accident rate.

The multivariate models developed to estimate functional relationships often differ in many respects. Variable definitions may not be identical; the models may not include the same set of variables; the mathematical form of the functions estimated may differ; the range of values found in the variables included may vary; and the precision of the estimated regression coefficients may vary. These factors and many others make it difficult to compare regression models, let alone formally synthesise their results by means of meta-analysis. Meta-analysts (Becker and Wu 2007, Card 2012) have therefore proposed a set of quite restrictive conditions that must be fulfilled for a meta-analysis of regression coefficients to make sense.

Regression coefficients will often be found to be incomparable and thus not lend themselves to meta-analysis. Fortunately, most studies that have investigated the relationship between access point density and accident rate are comparable, or can be made comparable by means of simple data edits or conversion of regression coefficients. It was thus feasible to perform a meta-analysis of 20 regression coefficients showing how the number of access points per kilometre of road is associated with accident rate.

Still, the analysis was not without problems. The funnel plot indicated a wide dispersion of estimates and two of the most precise estimates of the regression coefficient were initially found to be outlying, meaning that when they were omitted, the value of the summary regression coefficient changed significantly. This anomaly disappeared when a random-effects model of meta-analysis was applied. Qualitatively, there is great consistency in estimates, as 19 out of 20 regression coefficients indicate a positive association: the more access points, the higher the accident rate. Quantitatively, there was huge variation.

The summary estimate of the regression coefficient is statistically representative, in that 9 estimates are lower than it and 11 are higher. It is, in other words, located close to the middle of the distribution of the individual regression coefficients. It is also reassuring that the regression coefficients for access point density were found not to be influenced by how many covariates a model included and were stable over time. Finally, meta-regression found that it did not matter whether the regression coefficient for access point density was estimated in a model using accident rate as dependent variable or in a model using the number of accidents as dependent variable.

9 CONCLUSIONS

The main conclusions of the study presented in this paper are:

1. Studies of the relationship between access point density and accident rate have consistently found that accident rate increases as access point density increases.
2. Regression coefficients for access point density have been formally synthesised by means of meta-analysis. The summary estimate of the regression coefficient implies that accident rate increases by about 4 % when the number of access points per kilometre of road increases by one.

3. The summary regression coefficient was found to be insensitive to the number of covariates included in regression models and the publication year of a study.
4. It is feasible to perform an inverse-variance meta-analysis of regression coefficients when the coefficients refer to a variable which is identically defined in all studies even if the regression models may differ in other respects.

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Table 1:

Study (chronologically)	Authors	Country	Inclusion in meta-analysis
1	Jensen 1968	Norway	Yes, merged with other Norwegian studies before 1980 into a single study
2	Grimsgaard 1976	Norway	Yes, merged with other Norwegian studies before 1980 into a single study
3	Hvoslef 1977	Norway	Yes, merged with other Norwegian studies before 1980 into a single study
4	Amundsen 1979	Norway	Yes, merged with other Norwegian studies before 1980 into a single study
5	Grimsgaard 1979	Norway	Yes, merged with other Norwegian studies before 1980 into a single study
6	Hovd 1979	Norway	Yes, merged with other Norwegian studies before 1980 into a single study
7	Muskaug 1985	Norway	Yes, re-analysed by means of meta-regression to obtain relevant coefficients
8	Vogt and Bared 1998	United States	Yes, coefficients converted to metric scale
9	Wang, Hughes and Stewart 1998	United States	Yes, coefficients converted to metric scale
10	Brown and Tarko 1999	United States	Yes
11	Mouskos et al. 1999A	United States	Yes, coefficients from one of a total of ten models
12	Mouskos et al. 1999B	United States	No, duplicates Mouskos et al. 1999A
13	Papayannoulis et al. 1999	United States	Yes, coefficients converted to metric scale
14	Ivan, Wang and Bernardo 2000	United States	Yes, coefficients converted to metric scale
15	Hauer et al. 2004	United States	No, model of different form and standard error of coefficients not reported
16	Eisele and Frawley 2005	United States	Yes, relationship estimated based on data in Table 3 of the paper
17	Schultz, Lewis and Boschert 2007	United States	Yes, relationship estimated based on data in Figure 5 in the paper
18	Flintsch et al. 2008	United States	No, different definition of access point density and standard errors of coefficients not reported
19	Fitzpatrick et al. 2008	United States	Yes, coefficients converted to metric scale
20	Liu, Lu and Chen 2008	United States	No, different definition of access point density and different model form
21	Cafiso et al. 2010	Italy	Yes
22	Brimley et al. 2012	United States	Yes, coefficients converted to metric scale
23	Avelar et al. 2013	United States	No, different definition of access point density variable
24	Xu et al. 2013	United States	No, model of different form making coefficients incomparable to other studies
25	Huang et al. 2014	United States	Yes, data were re-analysed using negative binomial regression (see text)
26	Williamson and Chou 2014	United States	No, does not deal with access point density
27	Alluri et al. 2015	United States	No, not sufficient data about relevant variables and coefficients

Table 2:

Study	Dependent variable	Model type	Coefficients for access point density (original metric)	Standard error of coefficient	Re-analysis of study to prepare for meta-analysis
Jensen 1968	Accident rate	No model developed	Not estimated	Not estimated	Yes
Grimsgaard 1976	Accident rate	No model developed	Not estimated	Not estimated	Yes
Hvoslef 1977	Accident rate	No model developed	Not estimated	Not estimated	Yes
Amundsen 1979	Accident rate	No model developed	Not estimated	Not estimated	Yes
Grimsgaard 1979	Accident rate	No model developed	Not estimated	Not estimated	Yes
Hovd 1979	Accident rate	No model developed	Not estimated	Not estimated	Yes
Muskaug 1985	Accident rate	No model developed	Not estimated	Not estimated	Yes
Vogt and Bared 1998	Number of accidents	Generalised linear	0.0062	0.0034	No
Wang et al. 1998	Number of accidents	Generalised linear	0.034	0.008	No
Brown and Tarko 1999	Number of accidents	Generalised linear	0.0325; 0.0261	0.0078; 0.0081	No
Mouskos et al. 1999A	Accident rate	Linear additive	0.0444	0.0107	No
Papayannoulis et al. 1999	Accident rate	No model developed	Not estimated	Not estimated	Yes
Ivan et al. 2000	Number of accidents	Generalised linear	-0.01; 0.08	0.0117; 0.0073	No
Eisele and Frawley 2005	Accident rate	No model developed	Not estimated	Not estimated	Yes
Schultz et al. 2007	Accident rate	No model developed	Not estimated	Not estimated	Yes
Fitzpatrick et al. 2008	Number of accidents	Generalised linear	0.0801; 0.0161; 0.0205; 0.0051; 0.0044	0.0234; 0.0099; 0.0092; 0.0111; 0.0111	No
Cafiso et al. 2010	Number of accidents	Generalised linear	0.067	0.004	No
Brimley et al. 2012	Number of accidents	Generalised linear	0.0277	0.0181	No
Huang et al. 2014	Number of accidents	Generalised linear	0.087	0.0188	Yes

Table 3:

	Number of accidents by access point density				Injury accidents per million vehicle kilometres			
Study	**0-5**	**6-15**	**16-30**	**30-**	**0-5**	**6-15**	**16-30**	**30-**
Jensen 1968	2	44	73	169	0.11	0.76	1.24	2.24
Grimsgaard 1976	70	82	176	21	0.42	0.49	1.05	1.00
Hvoslef 1977	5	33	20	18	0.19	0.67	0.87	0.69
Amundsen 1979	323	766	536	262	0.20	0.30	0.40	0.70
Grimsgaard 1979	6	13	12	8	0.24	0.64	1.48	1.74
Hovd 1979	38	755	1046	65	0.30	0.29	0.49	0.72
Total or mean	444	1693	1863	543	0.243	0.327	0.557	1.208

Table 4:

Access points per km of road	Traffic volume (AADT) (number of injury accidents per million vehicle kilometres by AADT and access point density (Muskaug 1985, appendix)									
	0-299	**300-799**	**800-1499**	**1500-3999**	**4000-7999**	**8000-11999**	**12000-19999**	**20000-39999**	**40000-**	**All volumes**
0-5 (3)	0.32	0.24	0.24	0.22	0.20	0.21	0.13	0.17	0.04	0.21
6-10 (8)	0.53	0.34	0.30	0.27	0.24	0.21	0.22	0.19	0.04	0.27
11-15 (13)	0.77	0.33	0.36	0.30	0.23	0.24	0.27	0.30		0.29
16-30 (23)	0.67	0.59	0.44	0.38	0.35	0.29	0.27	0.38	0.11	0.38
30- (40)	1.15	0.94	0.71	0.51	0.43	0.35	0.31	0.81		0.47
City centre (70)		1.32	0.43	1.24	0.81	0.72	0.75	0.55		0.80
All densities	0.44	0.31	0.31	0.30	0.27	0.29	0.24	0.25	0.04	0.29

Entries are injury accidents per million vehicle kilometres. Empty cells are cells with no data

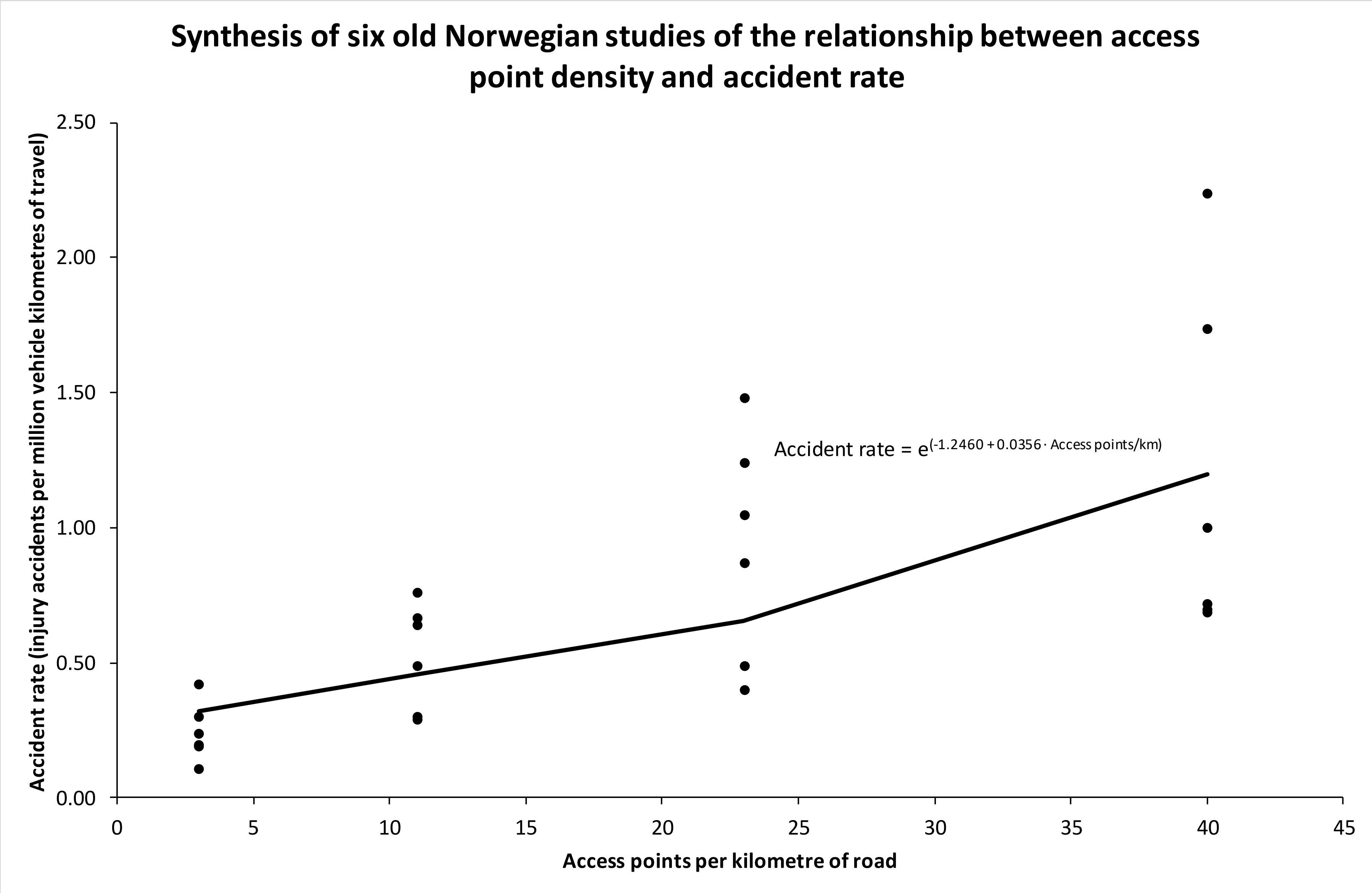
Table 5:

Terms	Coefficients	Standard errors	P-values
Constant term	-2.0407	2.1749	0.3481
Type of model	0.0224	0.0195	0.2502
Number of covariates	-0.0015	0.0024	0.5270
Publication year	0.0010	0.0011	0.3402

Table 6:

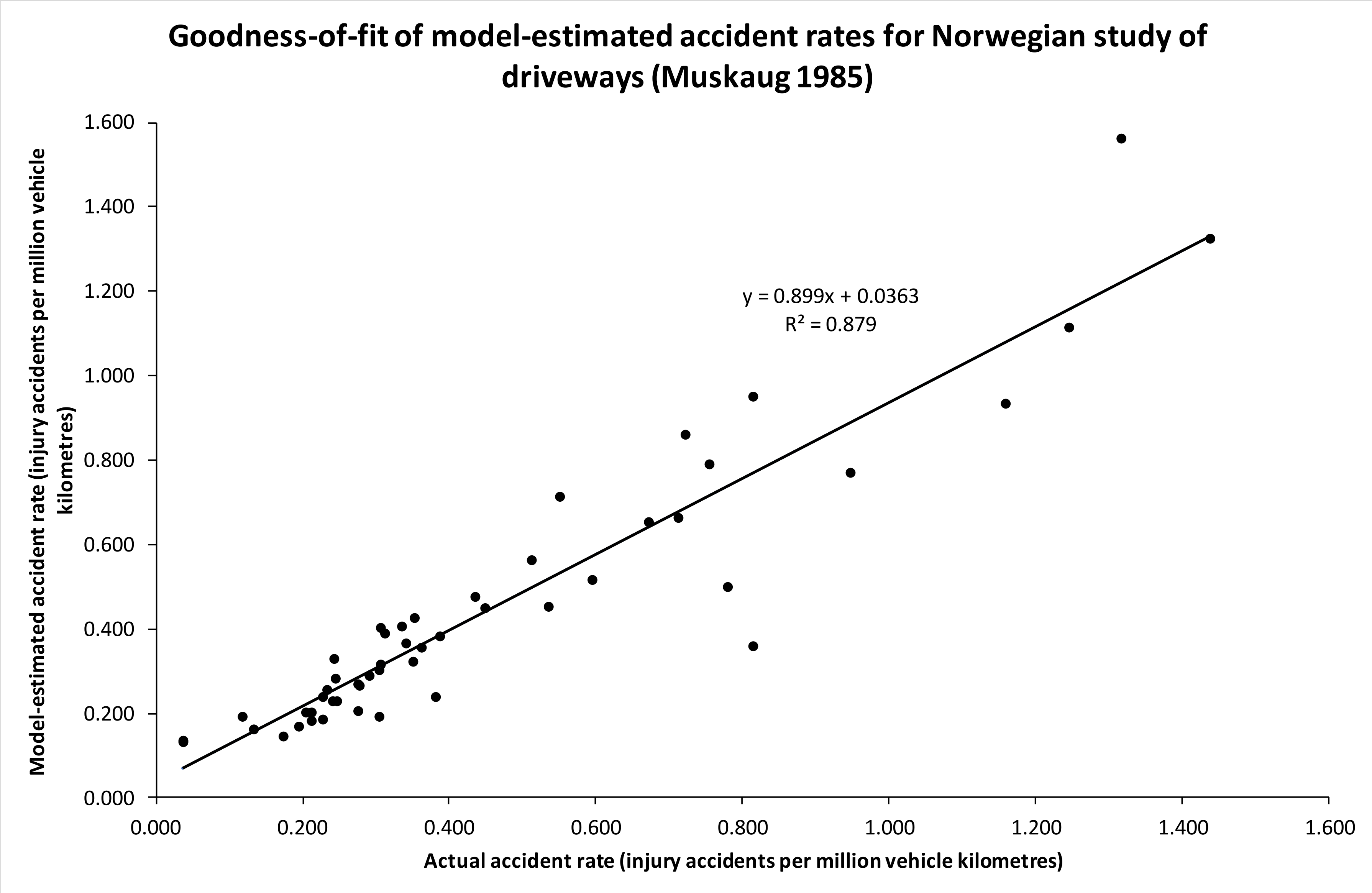
Estimate of coefficient	Fixed-effects weight	Estimate x weight	Difference	Rank	Difference	Rank	Difference	Rank
-0.01609	7305.136	-117.540	-0.04505	-16	-0.04240	-16	-0.04222	-16
0.00708	8116.224	57.463	-0.02188	-13	-0.01923	-13	-0.01905	-13
0.00821	8116.224	66.634	-0.02075	-12	-0.01810	-11	-0.01792	-11
0.00998	86505.190	863.322	-0.01898	-11	-0.01633	-9	-0.01615	-9
0.02330	510204.082	11887.755	-0.00566	-7	-0.00301	-5	-0.00283	-5
0.02414	45269.353	1092.802	-0.00482	-6	-0.00217	-4	-0.00199	-4
0.02574	62500.000	1608.750	-0.00322	-3	-0.00057	-3	-0.00039	-3
0.02590	10203.041	264.259	-0.00306	-2	-0.00041	-2	-0.00023	-2
0.02610	15092.153	393.905	-0.00286	-1	-0.00021	-1	-0.00003	-1
0.03250	16478.781	535.560	0.00354	4	0.00619	6	0.00637	6
0.03298	11814.745	389.650	0.00402	5	0.00667	7	0.00685	7
0.03560	18765.247	668.043	0.00664	8	0.00929	8	0.00947	8
0.04320	8734.387	377.326	0.01424	9	0.01689	10	0.01707	10
0.04457	3052.410	136.046	0.01561	10	0.01826	12	0.01844	12
0.05471	15625.000	854.844	0.02575	14	0.02840	14	0.02858	14
0.06700	62500.000	4187.500	0.03804	15	0.04069	15	0.04087	15
0.08544	2657.031	227.017	0.05648	17	0.05913	17	0.05931	17
0.12872	18765.247	2415.463	0.09976	18	0.10241	18	0.10259	18
0.12888	1826.284	235.371	0.09992	19	0.10257	19	0.10275	19
0.13998	2829.335	396.050	0.11102	20	0.11367	20	0.11385	20
Total	916359.867	26540.220	892939.002	23493.336	890281.971	23266.319		
Weighted mean		0.029		0.026		0.026		
Estimator L				3.49		4.21		
Estimator R				3		3		

Figure 1:



Synthesis of six old Norwegian studies of the relationship between access point density and accident rate
Accident rate (injury accidents per million vehicle kilometres of travel)
2.50
2.00
1.50
1.00
0.50
0.00
Accident rate = e(-1.2460 + 0.0356 · Access points/km)
0
5
10
15
20
25
30
35
40
45
Access points per kilometre of road

Figure 2:



Goodness-of-fit of model-estimated accident rates for Norwegian study of driveways (Muskaug 1985)
y = 0.899x + 0.0363
R² = 0.879
Model-estimated accident rate (injury accidents per million vehicle kilometres)
Actual accident rate (injury accidents per million vehicle kilometres)
0.000
0.200
0.400
0.600
0.800
1.000
1.200
1.400
1.600

Figure 3:

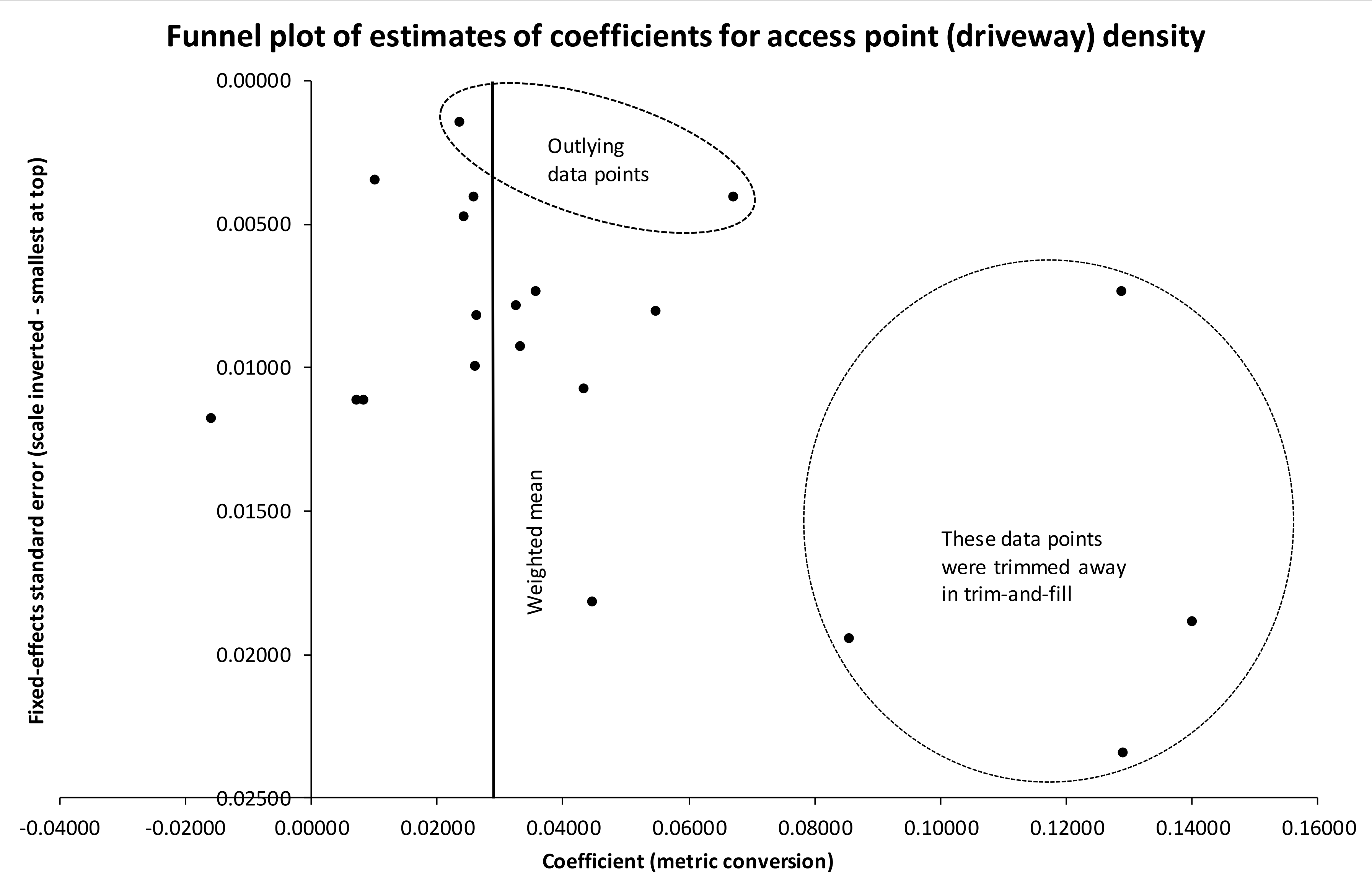

Funnel plot of estimates of coefficients for access point (driveway) density
0.00000
0.00500
0.01000
0.01500
0.02000
0.02500
-0.04000
-0.02000
0.00000
0.02000
0.04000
0.06000
0.08000
0.10000
0.12000
0.14000
0.16000
Fixed-effects standard error (scale inverted - smallest at top)
Coefficient (metric conversion)
Outlying data points
Weighted mean
These data points were trimmed away in trim-and-fill

Figure 4:

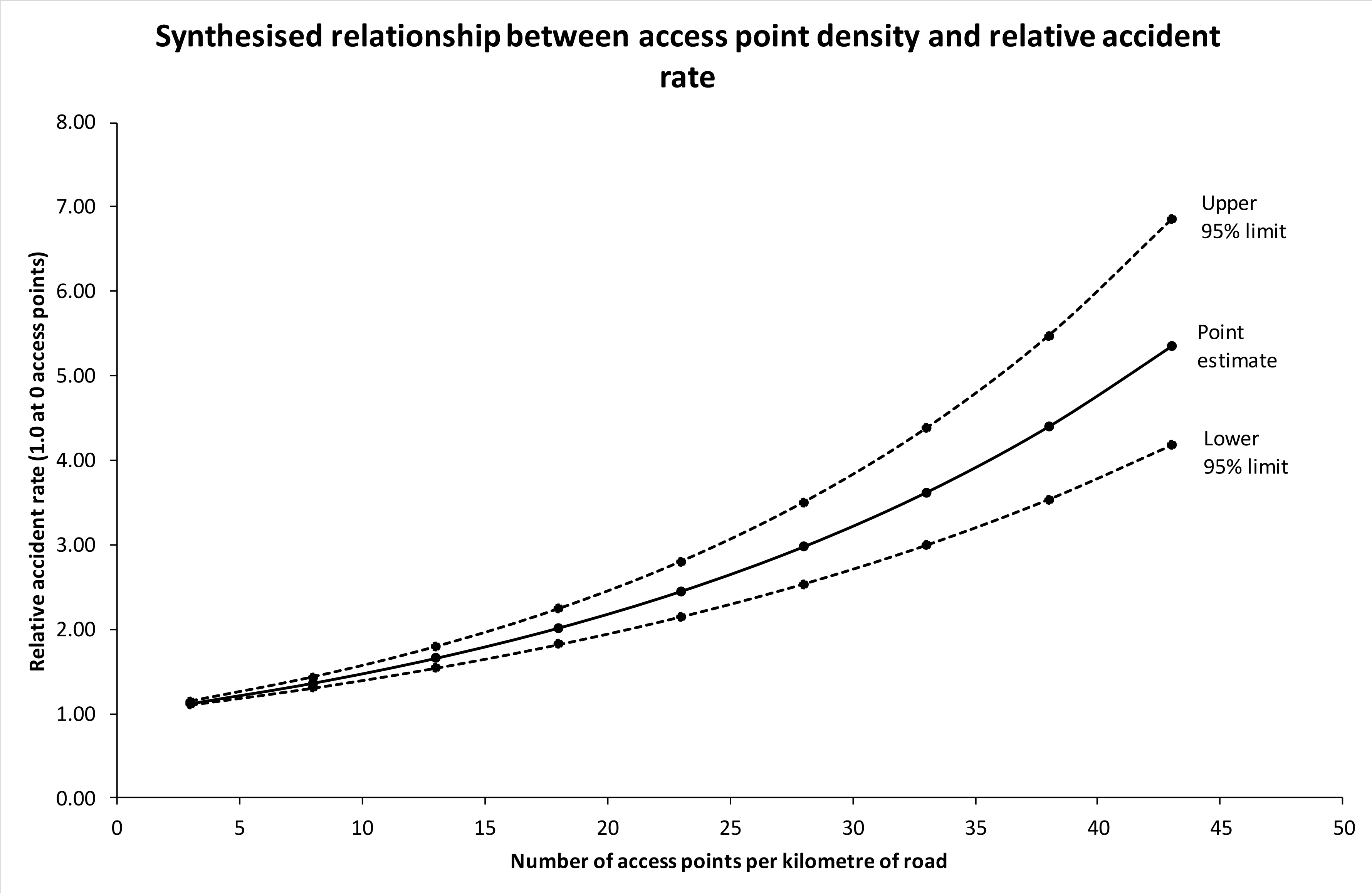

Synthesised relationship between access point density and relative accident rate
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Relative accident rate (1.0 at 0 access points)
0
5
10
15
20
25
30
35
40
45
50
Number of access points per kilometre of road
Upper 95% limit
Point estimate
Lower 95% limit

Figure 5:

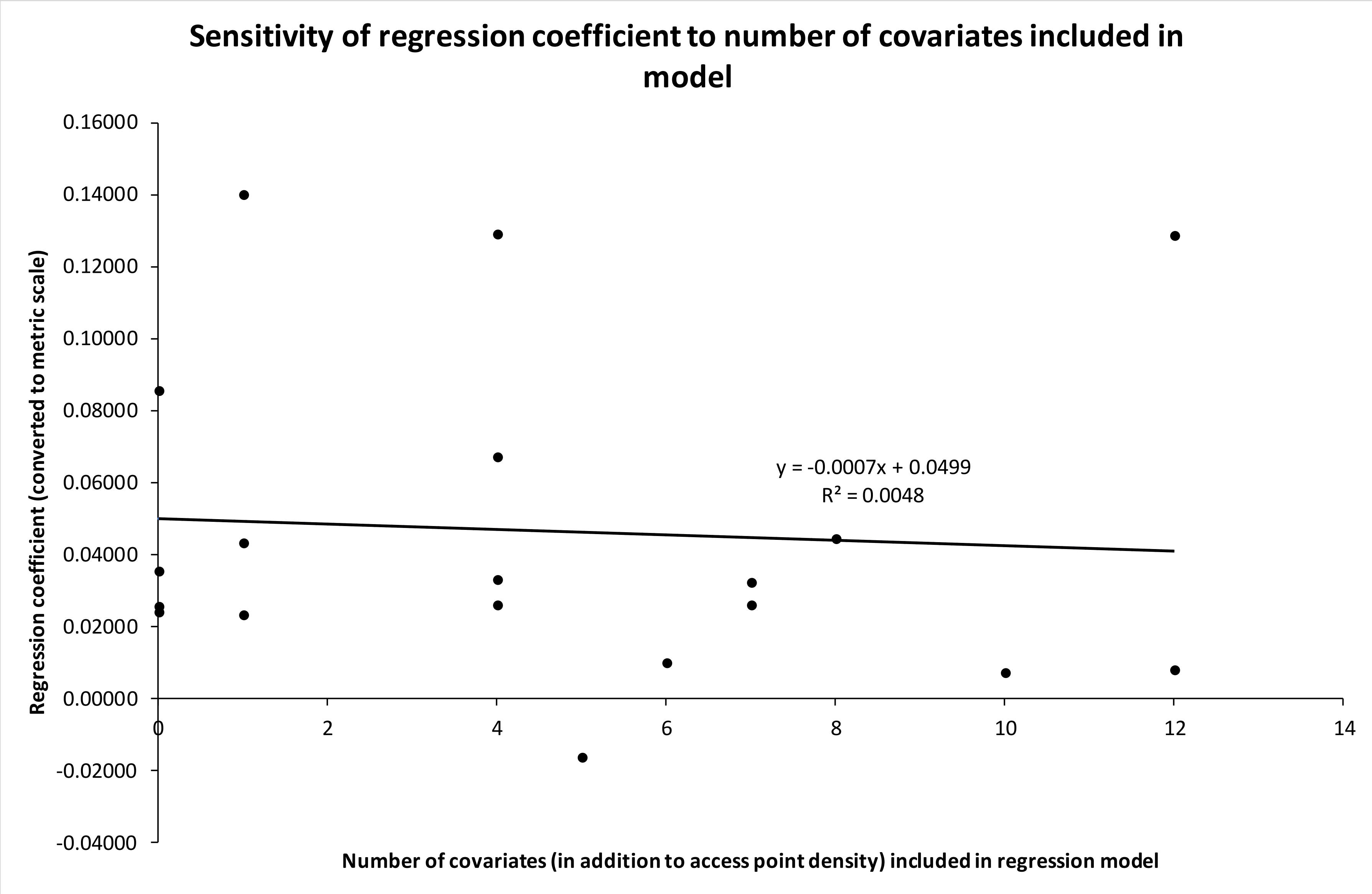
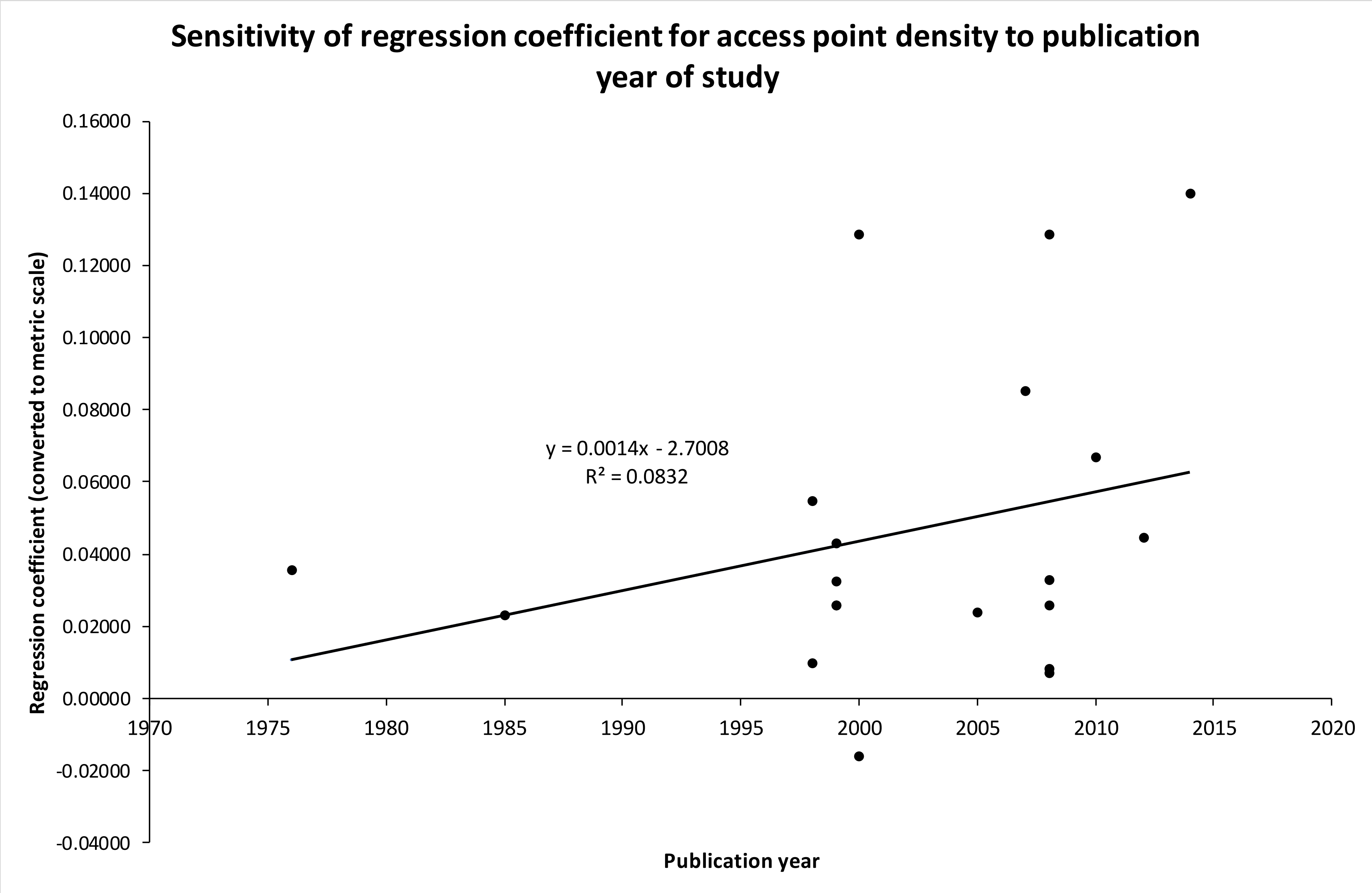

Sensitivity of regression coefficient to number of covariates included in model
Regression coefficient (converted to metric scale)
0.16000
0.14000
0.12000
0.10000
0.08000
0.06000
0.04000
0.02000
0.00000
-0.02000
-0.04000
0
2
4
6
8
10
12
14
y = -0.0007x + 0.0499
R² = 0.0048
Number of covariates (in addition to access point density) included in regression model

Figure 6:



Sensitivity of regression coefficient for access point density to publication year of study
0.16000
0.14000
0.12000
0.10000
0.08000
0.06000
0.04000
0.02000
0.00000
-0.02000
-0.04000
Regression coefficient (converted to metric scale)
y = 0.0014x - 2.7008
R² = 0.0832
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Publication year