Effects on road safety of converting intersections to roundabouts: A review of evidence from non-US studies

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ABSTRACT

This paper reports the results of a meta-analysis of studies reported outside the United States that have evaluated the effects on road safety of converting intersections to roundabouts. A total of 28 studies that provided 113 estimates of effect are included. State-of-the-art techniques of meta-analysis were applied to synthesize evidence from these evaluation studies. A meta-regression analysis was performed and the possible presence of publication bias was tested and adjusted for by means of the trim-and-fill method. The results show that roundabouts are associated with a reduction of 30 to 50% in the number of injury accidents. Fatal accidents are reduced by 50 to 70%. Effects on property damage accidents are highly uncertain, but in three leg intersections an increase will often occur. Evidence from the evaluation studies, although highly uncertain, suggest that the effect of roundabouts on injury accidents is greater in four leg intersections than in three leg intersections, and greater in intersections previously controlled by yield signs than in intersections previously controlled by traffic signals. Few studies have evaluated in detail the effects on safety of design parameters for roundabouts. Findings are inconsistent, but the majority of studies find that small roundabouts (a small diameter of the central traffic island) are safer than large roundabouts (a large diameter of the central traffic island).

Key words: Roundabout, road safety, evaluation study, meta-analysis

INTRODUCTION

This paper reviews evidence from studies conducted outside the United States concerning the effects on road safety of converting intersections to roundabouts, in which entering traffic is required to yield to circulating traffic. Recent US-studies (*1-3*) suggest that converting intersections to roundabouts can greatly reduce the number and severity of accidents. In order to develop design guidelines for roundabouts, however, effects on both safety and traffic operations need to be known in greater detail.

The objective of the paper is to summarize evidence from studies that have evaluated the effects on road safety of converting intersections to roundabouts, by giving weighted mean estimates of effect based on a meta-analysis of evaluation studies. The study approach used in this paper is very similar to that in a paper dealing with road safety effects of bypasses (*4*). A technical description of how a meta-analysis using the log-odds method is performed can be found in that paper. The main research problems to be answered in this paper are:

1. What is the best current estimate of the effects on the expected number of accidents and accident severity of converting intersections to roundabouts?
2. To what extent do the effects on road safety of converting intersections to roundabouts vary, depending on design features of the roundabouts?

STUDY RETRIEVAL AND ANALYSIS

Study retrieval

Studies were retrieved by means of a systematic literature survey. Details of this survey are given elsewhere (*5*). A total of 28 studies (*6-34*) reported outside the United States that have evaluated the effects on road safety of converting intersections to roundabouts were retrieved. This includes both studies published in scientific journals and a few unpublished studies. The studies were reported during the years from 1975 to 1997. Table 1 lists characteristics that were coded for each study for use in meta-analysis.

Statistical analysis of study findings

Each of the studies that were retrieved contains one or more estimates of the effects on road safety of roundabouts. These estimates of effect were combined by means of the log-odds method of meta-analysis *(35)*. This method is based on the assumption that each estimate of effect is stated in terms of an odds ratio. This is the case in, for example, before-and-after studies using a comparison group. Effects on safety in before-and-after studies using a comparison group are normally estimated in terms of the following odds ratio:

$$\text{Estimate of effect} = \frac{\left(\dfrac{\text{Number of accidents after conversion to roundabout}}{\text{Number of accidents before conversion to roundabout}}\right)}{\left(\dfrac{\text{Number of comparison group accidents after}}{\text{Number of comparison group accidents before}}\right)}$$

Unfortunately, not all studies that have evaluated the effects on safety of roundabouts have employed the same study design. Some studies are simple before-and-after studies, which do not include a comparison group. Other studies are comparative studies of accident rates (number of accidents per million entering vehicles) in various types of intersections, generally using the ratio of accident rates between roundabouts and other types of intersections to indicate safety effects. Table 2 lists all studies that were retrieved (*6-34*) and indicates the study design employed by each study. It also lists the results found in each study. The number of results reported in each study varied from 1 to 20.

According to the log-odds method of meta-analysis, each estimate of effect is assigned a statistical weight inversely proportional to its variance. The variance of the logarithm of the odds ratio is:

$$v_i = \frac{1}{A} + \frac{1}{B} + \frac{1}{C} + \frac{1}{D},$$

A, B, C, and D are the four numbers that enter the calculation of the odds ratio. In simple before-and-after studies, numbers C and D drop out. By the same token, the statistical weight assigned to an accident rate ratio is based on just the two accident numbers, not the number of entering vehicles that forms the denominator of each estimate of the accident rate. These approximations are not ideal, but reflect the fact that the size of the accident sample on which an estimate of effect is based varies within each study and between studies. In case of zero accidents, 0.5 was added to all four (or two) numbers used in estimating the statistical weight of a result.

There are two models for estimating a summary estimate of effect, based on a set of estimates: the fixed-effects model and the random-effects model (*36*). The fixed-effects model of analysis is based on the assumption that the variation in effects found in a set of estimates of effect is purely random, that is due to sampling variation only. The validity of this assumption can be tested statistically (the homogeneity test). If the test statistic indicates that there is systematic variation in effects, a random-effects model of analysis is used. In a random-effects model, the statistical weight assigned to each result is modified by including a component reflecting the amount of systematic variation in a set of estimates of effect. A technical description of these models of analysis is given in a paper by Elvik, Amundsen and Hofset (*4*).

A traditional meta-analysis identifies sources of variation in study findings by dividing the data set into subgroups according to these sources. The current data set contains 113 estimates of effect, based on 28 studies. This means that the number of estimates of effect is rapidly depleted once studies are divided into subgroups according to the study characteristics listed in Table 1. While the traditional approach to meta-analysis has been used in this paper, it has been supplemented by a meta-regression analysis (*37*). A meta-regression analysis is a multivariate analysis designed to estimate the effects on study findings of many variables, controlling for the effects of all other variables included in the analysis. An important feature of meta-regression is that each estimate of effect is weighted statistically in the manner explained above.

Limitations of meta-analysis

Meta-analysis, including meta-regression, has two basic limitations. The first one is that a meta-analysis cannot improve the quality of the evaluation studies it is based on. It is important to try to sort studies according to quality, in particular with respect to control for confounding variables. Ideally speaking, a numerical quality score ought to be assigned to each study; at present, however, no widely accepted system for rating numerically the quality of road safety evaluation studies exists. In the meta-analysis reported in this paper, five different study designs were identified. A variable describing study design was used in the meta-regression analysis.

A second limitation of meta-analysis is that it can be biased to the extent that it relies on published studies only. Publication bias is a potential source of error. Publication bias denotes the tendency not to publish studies whose findings go against conventional wisdom or are otherwise regarded as having little value. Techniques have been developed for diagnosing the presence of publication bias and trying to correct for it. In this paper one of these techniques, the trim-and-fill method (*38*), was used to test and adjust for publication bias. The trim-and-fill method is a non-parametric method for diagnosing and correcting for publication bias, based on the assumption that a funnel plot of results (see below) should be symmetric around the mean in the absence of publication bias. The trim-and-fill method trims away extreme data points from one tail of the funnel plot, until further trimming does not significantly affect the summary mean. A corresponding number of data points are then filled in at the opposite tail of the funnel plot, thus making it more symmetrical. Besides, as mentioned already, unpublished studies were included in the meta-analysis.

RESULTS

Exploratory analyses

A total of 113 estimates of effect were derived from 28 evaluation studies. An exploratory analysis was made in order to find the best way of summarizing and presenting the results of these studies. A previous review of these studies (*5*) has indicated that the effects of roundabouts vary greatly, depending on accident severity. Separate funnel graphs were therefore prepared for estimates of effect on injury accidents and estimates of effect on property damage only accidents. Figure 1 presents the funnel graph for injury accidents.

Each dot in the graph represents an estimate of effect. The horizontal axis denotes the size of the change in the number of accidents indicated by each estimate of effect. Please note the use of a logarithmic scale for the horizontal axis. The value of 1.0 indicates no effect. A value of 0.1 indicates a 90% accident reduction, while the value 10.0 indicates a ten-fold increase in accidents. The vertical axis shows the statistical weight assigned to each estimate of effect, according to a fixed-effects model of analysis.

It is seen that there is a very wide dispersion of estimates of effect. A total of 81 estimates of effect are shown in Figure 1. Ideally speaking, the contours of the outer data points in a funnel graph would form a symmetrical, bell-shaped curve. In Figure 1, such a pattern can be discerned, except for the uppermost data point in the figure, which appears to be located to the right of most of the other data points. Despite this, the overall pattern of the distribution of data points in Figure 1 is sufficiently orderly that it makes sense to estimate a weighted mean estimate of effect. A trim-and-fill analysis of the data points in Figure 1 resulted in the addition of ten new data points to the right in the figure. The new data points that were filled in had rather small statistical weights. Their addition did therefore not affect the summary estimate of effect very much. The random-effects weighted mean estimate of effect was a 43% accident reduction without the correction for publication bias, and a 37% accident reduction with the correction for publication bias.

Figure 2 shows a similar funnel graph for estimates of effect on property damage only accidents. There are 32 estimates in total. These are very widely spread, and no clear tendency is seen for estimates of effect based on large accident samples (top of diagram) to cluster more closely together than estimates of effect based on small accident samples (bottom of diagram). The distribution of data points in Figure 2 is so disorderly that it is doubtful that an overall summary estimate of effect of roundabouts on property damage only accidents would be very informative.

A trim-and-fill analysis of the data points in Figure 2 found no evidence of publication bias. Estimates of effect were stratified according to accident severity and the number of legs in converted intersections. The test for homogeneity of estimates of effect was applied to each subgroup. Results are reported in Table 3. As shown in Table 3, there were few estimates of effect for three leg intersections. In most of the categories listed in Table 3, significant heterogeneity of estimates of effect was found. It should be noted that the homogeneity test is known to have rather low power. The subsequent analyses relied on a random-effects model.

Results of traditional meta-analysis

Table 4 reports the results of a random-effects meta-analysis of before-and-after studies that have evaluated the effects on accidents of converting intersections to roundabouts. All summary estimates of effect presented in Table 4 refer to intersections that were previously controlled by yield signs.

The number of injury accidents is greatly reduced. For three leg intersections, the summary estimates of effect are based on few studies. There is more extensive evidence of safety effects for four leg intersections. The analysis shows that converting intersections to roundabouts greatly reduces both the number and severity of injury accidents. The reduction in accident severity is evident from the fact that the percentage reduction of the number of accidents is greater for fatal and serious injury accidents than for slight injury accidents.

The results presented in Table 4 show the limitations of a traditional approach to meta-analysis. Once estimates of effect are classified by two or more variables, the number of estimates of effect available for analysis in each cell of the table dwindles rapidly. In Table 4, estimates of effect are specified according to number of legs and accident severity. One would, however, like to learn how a number of design features of roundabouts, like the size of the central traffic island, influence their effects on safety. Meta-regression analysis allows for the estimation of effects for any conceivable combination of values on all variables that influence the effects of roundabouts on road safety.

It should be noted that the results presented in Table 4 are based on before-and-after studies only. The results of the comparative studies of accident rates differed from the results of the before-and-after studies. In most cases, the comparative studies found much smaller effects of roundabouts, and sometimes even found that an increase of the rate of injury accidents is associated with converting intersections to roundabouts. The effect of study design on estimates of effect therefore needs to be taken carefully into consideration when developing the best current estimates of the effects of roundabouts on road safety.

Results of meta-regression analysis

Meta-regression was run in two stages. The first stage included all variables listed in Table 1, except year of study publication. No statistically significant effects were found of variables representing the country in which the study was reported. This is reassuring, because it means that it is defensible to generalize the results of evaluation studies across countries. In the second stage, country variables (each country was represented by a dummy variable) were therefore omitted. Results of the meta-regression, stated in terms of the best current estimates of the percentage change in the number of accidents associated with converting intersections to roundabouts are given in Table 5.

Table 5 gives effects of constructing conventional roundabouts for each level of accident severity, depending on the number of legs in an intersection and the type of traffic control before conversion to a roundabout. The estimates given in Table 5 are based on coefficients that apply to before-and-after studies that have controlled for long-term trends and regression-to-the-mean. This study design was selected as the best one among the study designs that are found in this data set. A

95% confidence interval is given for each estimate of effect. Confidence intervals were estimated by means a computer program written specifically for the purpose.

According to the estimates of effect given in Table 5, roundabouts reduce both the number and severity of injury accidents. The largest reductions are found for fatal accidents, the smallest reductions for injury accidents for which injury severity was not stated. The number of property damage only accidents is found to increase in three of the four cases included in Table 5. Roundabouts appear to be more effective in reducing injury accidents in four leg intersections than in three leg intersections. Moreover, roundabouts appear to be more effective in reducing accidents in intersections that were previously controlled by yield signs than in signalized intersections. Traffic control by means of stop signs is rather uncommon outside the United States. All estimates of effect presented in Table 5 are surrounded by very wide confidence intervals. Possible reasons for this are discussed below. Moreover, these estimates have not been adjusted for publication bias.

Effects of roundabout design features

Most of the studies that have evaluated the effects on converting intersections to roundabouts do not report very detailed information on roundabout design features. It is therefore not possible to develop detailed design standards for roundabouts based on these studies. As an example, the size of the central traffic island can only be roughly described, as shown in Table 1, using the categories mini, small, conventional and large. According to the meta-regression analysis, conventional roundabouts have the largest effects on accidents. A supplementary literature search was made in order to identify studies that have examined the effects of roundabout design features more in detail. The following studies were found:

Cedersund 1983, Sweden (*9*)
Maycock and Hall 1984, Great Britain (*39*)
Brüde and Larsson 1999, Sweden (*40*)
Tran 1999, Norway (*41*)
Jørgensen and Jørgensen 2002, Denmark (*42*)

The design parameters that have been studied include number of legs, size of the central traffic island, width of approach lanes, width of the circular lanes inside the roundabout and angle between approaches to the roundabout. The most frequently studied design parameter is the size of the central traffic island.

Cedersund (*9*) studied how accident rates in roundabouts were influenced by traffic volume (AADT), proportion of traffic entering from the minor road, number of legs, speed limit and diameter of the central traffic island. The data included 102 roundabouts. No clear relationship was found between diameter of the central traffic island and accident rate. Most of the roundabouts were large, and had a central traffic island with a diameter of more than 40 meters.

Maycock and Hall (*39*) studied how a number of design parameters for roundabouts influenced the number of accidents by means of negative binomial regression models. Despite its age, this study remains valuable today because it employed a sophisticated technique of analysis. No clear effect on accident rate of the diameter of the central traffic island was found.

The studies of Brüde and Larsson (*40*) Tran (*41*) and Jørgensen and Jørgensen (*42*) all found that there is a positive relationship between the size of the central traffic island and accident rate. The larger the central traffic island, the higher becomes the accident rate. In general, the effects on accident rate of other design parameters appear to be quite small. The four factors that appear to have the strongest effect on accident rates in roundabouts are: total traffic volume, proportion of vehicles entering from the minor road, speed limit, and number of legs.

DISCUSSION

Many studies have evaluated the effects on safety of converting intersections to roundabouts and the effects of various design parameters for roundabouts on the accident rate in roundabouts. In this paper, state-of-the-art techniques of meta-analysis have been employed in order to summarize evidence from these studies. The results of the meta-analysis are, however, somewhat disappointing. There are three main reasons for saying so.

This first reason is that many of the studies that have evaluated the effects on road safety of converting intersections to roundabouts have employed study designs that are known not to provide sufficient control for confounding factors. Six of the twenty-eight studies listed in Table 2 are simple before-and-after studies that did not control for such potentially important confounding factors as long-term trends and regression-to-the-mean. Only three studies were before-and-after studies that controlled for long-term trends and regression-to-the-mean. As far as the comparative studies are concerned, these studies ought ideally speaking to control for all factors that may influence intersection accident rates, including traffic volume (accident rates tend to depend on volume), number of legs, type of traffic control, speed limit, proportion of traffic entering from the minor road or roads, the presence of facilities for pedestrians and cyclists, and so on. Most of the comparative studies have controlled for at least some of these factors, but no study has controlled for all of them. Based on what is known about how various confounding factors can influence study findings (*43*), before-and-after studies controlling for long-term trends and regression-to-the-mean were rated as most convincing.

The second weakness of the present study is that it does not add very much to previous knowledge concerning the effects on road safety of design parameters for roundabouts. The main reason for this is that most studies do not provide detailed descriptions of roundabout design. A few studies have tried to determine the effects of some design parameters. Unfortunately, the findings of these studies are conflicting, and the studies employed rather different techniques of analysis that do not lend themselves to synthesis by means of meta-analysis. A generous interpretation of the findings of these studies is that small roundabouts appear to have lower accident rates than large roundabouts.

A third shortcoming of this study is related to the limitations of current techniques of meta-analysis. Meta-regression was used, because it is in principle superior to a traditional subgroup analysis by being able to control for a large number of potentially confounding variables at the same time. Five variables were included in the main analysis (previous type of traffic control, number of legs, size of roundabout, study design, and accident severity). Given the fact that there were 113 estimates of effect in total, using five variables in a meta-regression does not seem excessive. However, the number of combinations of values for the five variables is 400 (2 x 2 x 4 x 5 x 5). This number is well in excess of the number of observations (113) used to fit the multivariate model, indicating that the model is underdetermined by the data (since not all 400 logically possible combinations of values are found in the data set). Most of the coefficients were indeed not statistically significant, and the coefficient of determination for the final model (not including country variables) was .375 (adjusted R-squared). On top of this, the pattern of covariance between the variables included in the model led to very large confidence intervals for the estimates of effect based on the meta-regression. None of the twenty estimates presented in Table 5 were statistically significant at the 5% level.

Despite these limitations, some useful results have emerged from the study. There is little reason to doubt that converting intersections controlled by yield signs or traffic signals to roundabouts will in most cases reduce the number and severity of injury accidents. The effect on property damage only accidents is very uncertain; an increase in these accidents cannot be ruled out. Although highly uncertain, the evidence indicates that roundabouts have a greater effect on safety in four leg intersections than in three leg intersections, and a greater effect on safety in intersections controlled by yield signs than in intersections controlled by traffic signals.

CONCLUSIONS

The main conclusions of the research reported in this paper can be summarized in these points:

1. Evidence from 28 studies reported outside the United States, containing a total of 113 estimates of the effects of roundabouts on road safety has been synthesized by means of meta-analysis. Meta-regression relying on a random-effects model was performed. Publication bias was tested and adjusted for by means of the trim-and-fill method.
2. Roundabouts were found to reduce the number of injury accidents. For all injury accidents combined, the best current estimate of the effect of converting intersections to roundabouts is an accident reduction of 30-50%.

3. Roundabouts reduce the severity of injury accidents. The number of fatal accidents is reduced by about 50 to 70%, depending on the previous type of traffic control and the number of legs in the intersections.
4. The effect of roundabouts on property damage only accidents is highly uncertain and has been found to vary greatly. An increase of the number of property-damage-only accidents cannot be ruled out, in particular in three leg intersections.
5. Evidence suggests that converting intersections to roundabouts has a greater effect on injury accidents in four leg intersections than in three leg intersections, and a greater effect in yield-controlled intersections than in signal-controlled intersections. This evidence is highly uncertain and suggestive only.
6. There are few detailed studies of the effects on safety of various design parameters for roundabouts. The most frequently studied design parameter is the diameter of the central traffic island. The majority of the studies that have evaluated the effect of this design parameter find that a small central island is associated with a low injury accident rate. However, such a tendency has not been found in all studies.

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FIGURE 1:

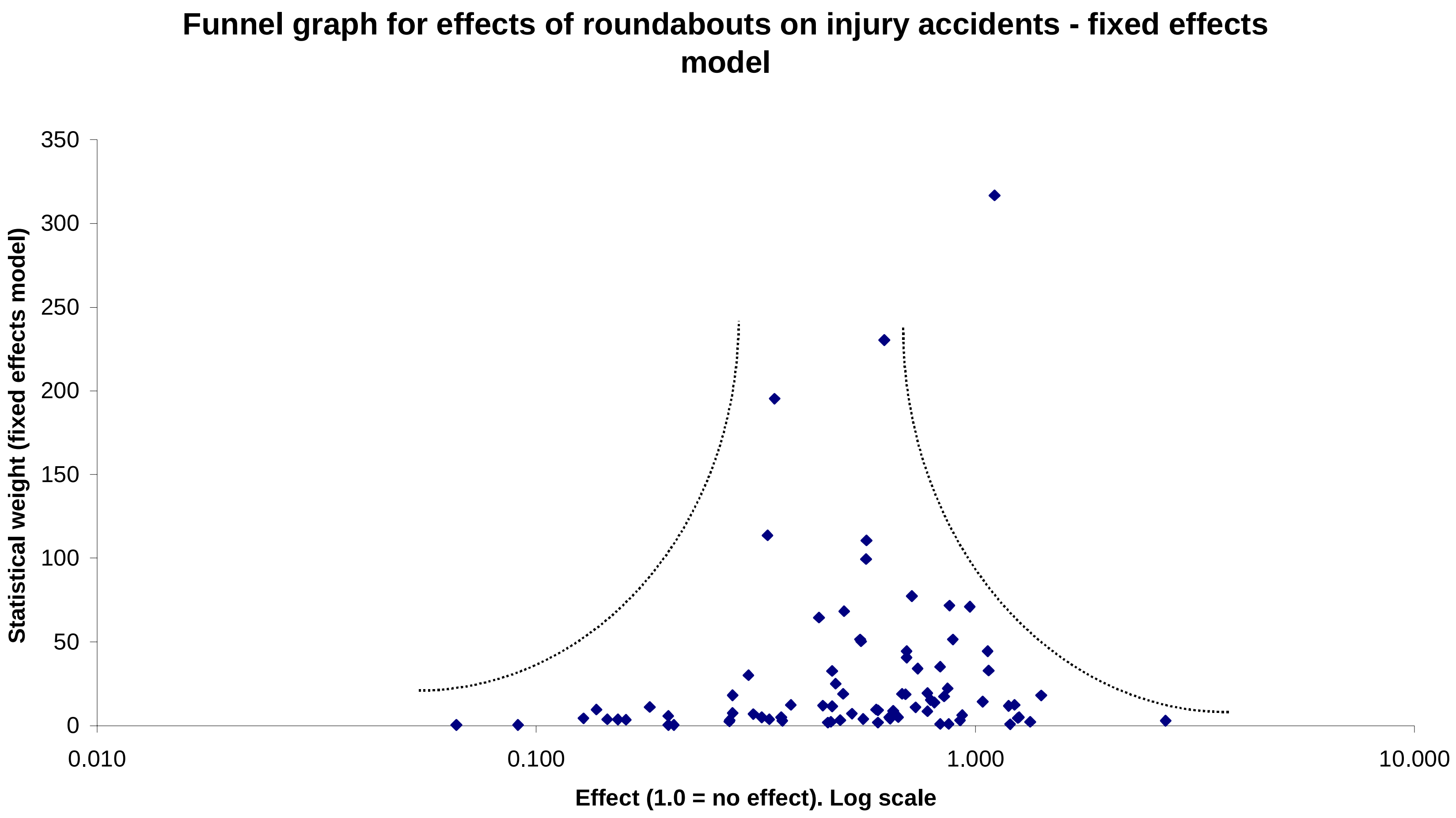
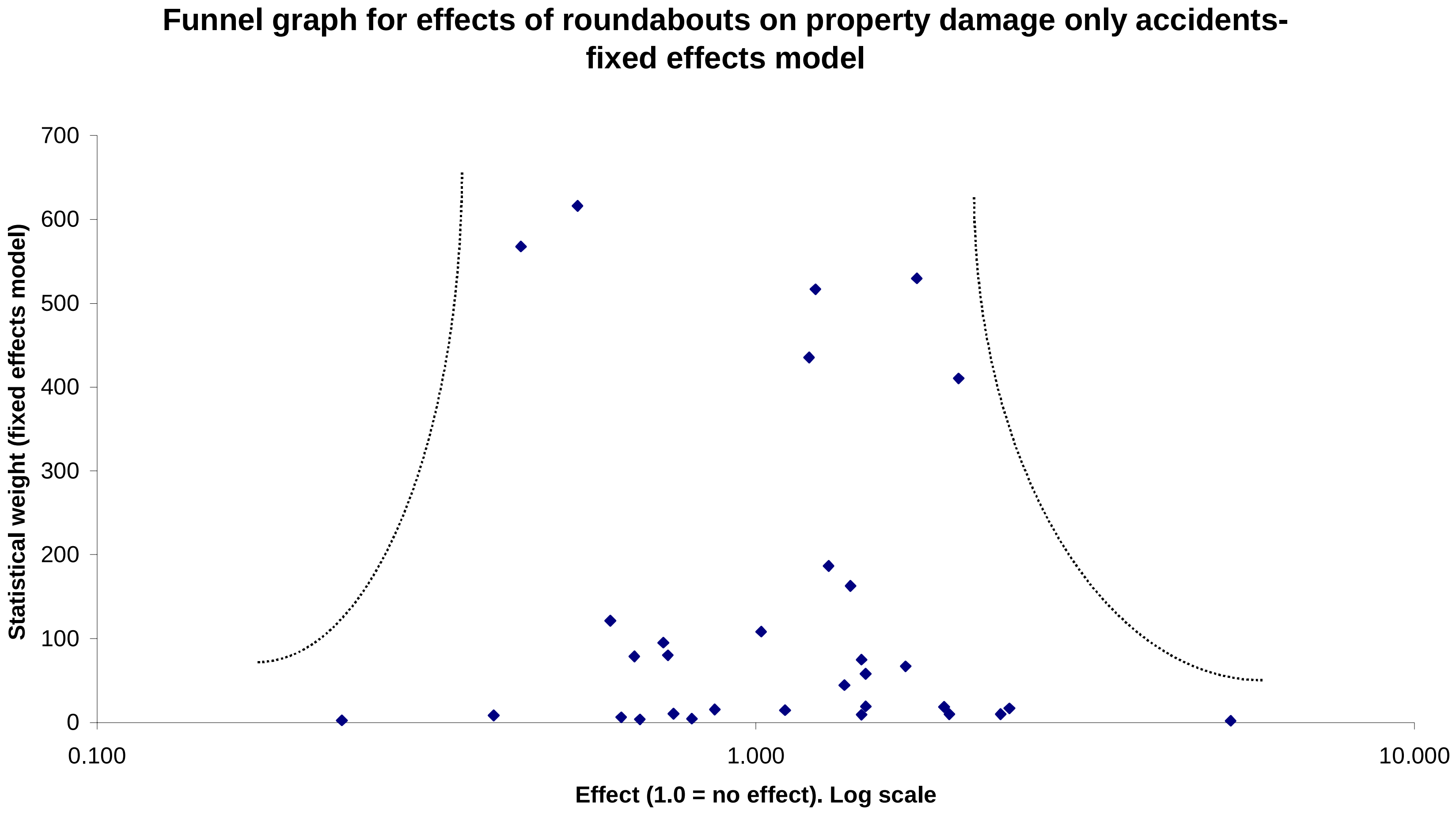

Funnel graph for effects of roundabouts on injury accidents - fixed effects model
Statistical weight (fixed effects model)
350
300
250
200
150
100
50
0
0.010
0.100
1.000
10.000
Effect (1.0 = no effect). Log scale

FIGURE 2:



Funnel graph for effects of roundabouts on property damage only accidents-
fixed effects model
700
600
500
400
300
200
100
0
Statistical weight (fixed effects model)
0.100
1.000
10.000
Effect (1.0 = no effect). Log scale

TABLE 1:
Study characteristics coded for meta-analysis

Study characteristics	Values of characteristics
Publication year	1975 through 1997
Country	Australia, Denmark, Germany, Great Britain, Netherlands, Norway, Sweden, Switzerland
Study design	(1) Simple before-and-after study (no comparison group and no data on traffic volume)
	(2) Before-and-after study containing data on traffic volume before-and-after
	(3) Before-and-after study using comparison group to control for general trends
	(4) Before-and-after study controlling for general trends and regression-to-the-mean
	(5) Comparative study of accident rates in roundabouts and other types of intersections
Previous type of traffic control	(1) Yield signs or (2) Traffic signals
Number of legs	3 or 4 or a decimal number (< 3.5 set to 3 in analysis; 3.5 or more set to 4 in analysis)
Diameter of central traffic island	(1) Mini (less than about 5 meters)
	(2) Small (about 5 to 15 meters)
	(3) Conventional (about 15 to 30 meters)
	(4) Large (more than about 30 meters)
Accident severity	(1) Fatal accident, (2) Serious injury accident, (3) Slight injury accident (4) Injury accident, severity not stated, (5) Property damage only

TABLE 2:
List of studies retrieved and results of each study by accident severity (chronological order)

Authors	Year	Country	Study design	Accident severity	Percentage change in the number of accidents
Lalani (6)	1975	Great Britain	Simple before-and-after	Injury (all severities)	-30
Lalani (6)	1975	Great Britain	Simple before-and-after	Injury (all severities)	-45
Green (7)	1977	Great Britain	Before-and-after, controlling for general trends	Serious injury	-35
Green (7)	1977	Great Britain	Before-and-after, controlling for general trends	Slight injury	-26
Green (7)	1977	Great Britain	Before-and-after, controlling for general trends	Serious injury	-55
Green (7)	1977	Great Britain	Before-and-after, controlling for general trends	Slight injury	-30
Green (7)	1977	Great Britain	Before-and-after, controlling for general trends	Serious injury	-32
Green (7)	1977	Great Britain	Before-and-after, controlling for general trends	Slight injury	-28
Green (7)	1977	Great Britain	Before-and-after, controlling for general trends	Serious injury	-62
Green (7)	1977	Great Britain	Before-and-after, controlling for general trends	Slight injury	-13
Lahrmann (8)	1981	Denmark	Comparative study of accident rates in various types of intersections	Injury (all severities)	+7
Lahrmann (8)	1981	Denmark	Comparative study of accident rates in various types of intersections	Injury (all severities)	-11
Lahrmann (8)	1981	Denmark	Before-and-after, controlling for general trends	Injury (all severities)	-93
Lahrmann (8)	1981	Denmark	Before-and-after, controlling for general trends	Property-damage-only	+426

TABLE 2:
List of studies retrieved and results of each study by accident severity (chronological order), continued

Authors	Year	Country	Study design	Accident severity	Percentage change in the number of accidents
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Serious injury	+26
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Slight injury	+4
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+69
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Serious injury	+171
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Slight injury	+19
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+47
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Fatal injury	+20
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Serious injury	-21
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Slight injury	-45
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+39
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Fatal injury	+33
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Serious injury	+7
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Slight injury	-43
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+23
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Serious injury	-72
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Slight injury	-82
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	-22
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Serious injury	-40
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Slight injury	-70
Cedersund (9,10)	1983	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+2

TABLE 2:
List of studies retrieved and results of each study by accident severity (chronological order), continued

Authors	Year	Country	Study design	Accident severity	Percentage change in the number of accidents
Senneset (11)	1983	Norway	Before-and-after, data on traffic volume	Injury (all severities)	-36
Brüde and Larsson (12)	1985	Sweden	Before-and-after, controlling for trends and regression-to-the-mean	Injury (all severities)	-31
Johannessen (13)	1985	Norway	Comparative study of accident rates in various types of intersections	Injury (all severities)	-37
Johannessen (13)	1985	Norway	Comparative study of accident rates in various types of intersections	Injury (all severities)	-69
Hall and McDonald (14)	1988	Great Britain	Comparative study of accident rates in various types of intersections	Serious injury	-3
Hall and McDonald (14)	1988	Great Britain	Comparative study of accident rates in various types of intersections	Slight injury	+11
Hall and McDonald (14)	1988	Great Britain	Comparative study of accident rates in various types of intersections	Serious injury	-17
Hall and McDonald (14)	1988	Great Britain	Comparative study of accident rates in various types of intersections	Slight injury	-44
Nygaard (15)	1988	Norway	Before-and-after, controlling for general trends	Injury (all severities)	-72
Giæver (16)	1990	Norway	Comparative study of accident rates in various types of intersections	Injury (all severities)	-40
Giæver (16)	1990	Norway	Comparative study of accident rates in various types of intersections	Injury (all severities)	-50
Giæver (16)	1990	Norway	Comparative study of accident rates in various types of intersections	Property-damage-only	+45
Tudge (17)	1990	Australia	Before-and-after, controlling for general trends	Fatal injury	-85
Tudge (17)	1990	Australia	Before-and-after, controlling for general trends	Non-fatal injury	-65
Tudge (17)	1990	Australia	Before-and-after, controlling for general trends	Property-damage-only	-56
Van Minnen (18)	1990	Netherlands	Simple before-and-after	Fatal injury	-79
Van Minnen (18)	1990	Netherlands	Simple before-and-after	Serious injury	-85
Van Minnen (18)	1990	Netherlands	Simple before-and-after	Slight injury	-86
Van Minnen (18)	1990	Netherlands	Simple before-and-after	Property-damage-only	-40

TABLE 2:
List of studies retrieved and results of each study by accident severity (chronological order), continued

Authors	Year	Country	Study design	Accident severity	Percentage change in the number of accidents
Jørgensen (19)	1991	Denmark	Simple before-and-after	Injury (all severities)	-22
Jørgensen (19)	1991	Denmark	Comparative study of accident rates in various types of intersections	Property-damage-only	-13
Jørgensen (19)	1991	Denmark	Comparative study of accident rates in various types of intersections	Injury (all severities)	+23
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Injury (all severities)	-17
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Injury (all severities)	-13
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Injury (all severities)	-56
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Injury (all severities)	-50
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Injury (all severities)	-67
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Injury (all severities)	-64
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+135
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+97
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+103
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+76
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+143
Brüde and Larsson (20)	1992	Sweden	Comparative study of accident rates in various types of intersections	Property-damage-only	+93
Dagersten (21)	1992	Switzerland	Simple before-and-after	Injury (all severities)	-54
Dagersten (21)	1992	Switzerland	Simple before-and-after	Property-damage-only	-25
Holzwarth (22)	1992	Germany	Simple before-and-after	Injury (all severities)	-8
Holzwarth (22)	1992	Germany	Simple before-and-after	Injury (all severities)	-44

TABLE 2:
List of studies retrieved and results of each study by accident severity (chronological order), continued

Authors	Year	Country	Study design	Accident severity	Percentage change in the number of accidents
Hydén, Odelid, Várhelyi (23)	1992	Sweden	Simple before-and-after	Injury (all severities)	-7
Hydén, Odelid, Várhelyi (23)	1992	Sweden	Simple before-and-after	Property-damage-only	+45
Jørgensen, Jørgensen (24)	1992	Denmark	Before-and-after, controlling for general trends	Fatal injury	-80
Jørgensen, Jørgensen (24)	1992	Denmark	Before-and-after, controlling for general trends	Serious injury	-48
Jørgensen, Jørgensen (24)	1992	Denmark	Before-and-after, controlling for general trends	Slight injury	-27
Jørgensen, Jørgensen (24)	1992	Denmark	Before-and-after, controlling for general trends	Property-damage-only	+47
Jørgensen, Jørgensen (24)	1992	Denmark	Before-and-after, controlling for general trends	Fatal injury	-91
Jørgensen, Jørgensen (24)	1992	Denmark	Before-and-after, controlling for general trends	Serious injury	-87
Jørgensen, Jørgensen (24)	1992	Denmark	Before-and-after, controlling for general trends	Slight injury	-80
Jørgensen, Jørgensen (24)	1992	Denmark	Before-and-after, controlling for general trends	Property-damage-only	-60
Kristiansen (25)	1992	Norway	Before-and-after, controlling for general trends	Injury (all severities)	-72
Kristiansen (25)	1992	Norway	Before-and-after, controlling for general trends	Property-damage-only	+29
Schnüll, Haller, Lübke (26)	1992	Germany	Before-and-after, data on traffic volume	Injury (all severities)	-40
Schnüll, Haller, Lübke (26)	1992	Germany	Before-and-after, data on traffic volume	Property-damage-only	-20
Schnüll, Haller, Lübke (26)	1992	Germany	Before-and-after, data on traffic volume	Injury (all severities)	+25
Schnüll, Haller, Lübke (26)	1992	Germany	Before-and-after, data on traffic volume	Property-damage-only	-33
Brilon, Stuwe, Drews (27)	1993	Germany	Before-and-after, data on traffic volume	Injury (all severities)	-52
Brilon, Stuwe, Drews (27)	1993	Germany	Before-and-after, data on traffic volume	Property-damage-only	-26
Schoon, Van Minnen (28)	1993	Netherlands	Simple before-and-after	Injury (all severities)	-66
Schoon, Van Minnen (28)	1993	Netherlands	Simple before-and-after	Property-damage-only	-46

TABLE 2:
List of studies retrieved and results of each study by accident severity (chronological order), continued

Authors	Year	Country	Study design	Accident severity	Percentage change in the number of accidents
Voss (29)	1994	Germany	Comparative study of accident rates in various types of intersections	Serious injury	-51
Voss (29)	1994	Germany	Comparative study of accident rates in various types of intersections	Slight injury	-15
Voss (29)	1994	Germany	Comparative study of accident rates in various types of intersections	Property-damage-only	-35
Voss (29)	1994	Germany	Comparative study of accident rates in various types of intersections	Serious injury	-66
Voss (29)	1994	Germany	Comparative study of accident rates in various types of intersections	Slight injury	-13
Voss (29)	1994	Germany	Comparative study of accident rates in various types of intersections	Property-damage-only	-28
Voss (29)	1994	Germany	Before-and-after, data on traffic volume	Serious injury	-64
Voss (29)	1994	Germany	Before-and-after, data on traffic volume	Slight injury	-19
Voss (29)	1994	Germany	Before-and-after, data on traffic volume	Property-damage-only	+36
Jørgensen, Jørgensen (30)	1994	Denmark	Before-and-after, controlling for trends and regression-to-the-mean	Injury (all severities)	-53
Jørgensen, Jørgensen (30)	1994	Denmark	Before-and-after, controlling for trends and regression-to-the-mean	Property-damage-only	+11
Jørgensen, Jørgensen (30)	1994	Denmark	Before-and-after, controlling for trends and regression-to-the-mean	Injury (all severities)	-84
Jørgensen, Jørgensen (30)	1994	Denmark	Before-and-after, controlling for trends and regression-to-the-mean	Property-damage-only	-76
Seim (31)	1994	Norway	Before-and-after, controlling for general trends	Injury (all severities)	-36
Huber and Bühlmann (32)	1994	Switzerland	Before-and-after, controlling for general trends	Fatal injury	-72
Huber and Bühlmann (32)	1994	Switzerland	Before-and-after, controlling for general trends	Non-fatal injury	-28
Huber and Bühlmann (32)	1994	Switzerland	Before-and-after, controlling for general trends	Property-damage-only	+21

TABLE 2:
List of studies retrieved and results of each study by accident severity (chronological order), continued

Authors	Year	Country	Study design	Accident severity	Percentage change in the number of accidents
Oslo Veivesen (33)	1995	Norway	Before-and-after, controlling for general trends	Serious injury	-33
Oslo Veivesen (33)	1995	Norway	Before-and-after, controlling for general trends	Slight injury	-53
Giæver (34)	1997	Norway	Before-and-after, controlling for trends and regression-to-the-mean	Serious injury	-53
Giæver (34)	1997	Norway	Before-and-after, controlling for trends and regression-to-the-mean	Slight injury	+41

TABLE 3:
Summary of amount of evidence available for meta-analysis

Number of legs	Accident severity	Number of estimates of effect	Proportion of statistical weights, fixed effects model	Homogeneity statistic (Q)	Exact P-value for Q-statistic (to three decimal places)
3	Fatal	0	0.000	Not applicable	Not applicable
	Serious injury	5	0.005	9.815	0.044
	Slight injury	5	0.018	8.928	0.063
	Injury, severity not stated	6	0.006	7.074	0.215
	Property damage only	5	0.050	7.292	0.121
4	Fatal	7	0.002	8.938	0.177
	Serious injury	15	0.035	48.533	0.000
	Slight injury	15	0.133	163.507	0.000
	Injury, severity not stated	28	0.151	132.710	0.000
	Property damage only	27	0.600	1172.832	0.000

TABLE 4:
Best estimates of effects of converting yield intersections to roundabouts – random effects meta-analysis of before-and-after studies

		Percentage change of the number of accidents – before-and-after studies of intersections that previously were controlled by yield signs		
Number of legs	Accident severity	Number of estimates of effect	Best estimate	95% confidence interval
3	Serious injury	3	-48	(-74, +4)
	Slight injury	3	-15	(-37, +16)
	Injury, severity not stated	2	-72	(-83, -53)
	Property damage only	1	+29	(+1, +65)
4	Fatal	5	-81	(-93, -50)
	Serious injury	6	-61	(-76, -39)
	Slight injury	6	-54	(-69, -32)
	Injury, severity not stated	19	-47	(-56, -34)
	Property damage only	16	-18	(-39, +11)

TABLE 5:
Estimates of effects of converting intersections to roundabouts based on meta-regression analysis. Estimates based on before-and-after studies controlling for long-term trends and regression-to-the-mean, not adjusted for publication bias

			Percentage change of the number of accidents	
Number of legs	Type of traffic control	Accident severity	Best estimate	95% confidence interval
3	Yield	Fatal	-49	(-97, +708)
		Injury, severity not stated	-29	(-83, +183)
		Serious injury	-33	(-87, +238)
		Slight injury	-31	(-85, +216)
		Property damage only	+37	(-68, +487)
	Traffic signals	Fatal	-42	(-97, +928)
		Injury, severity not stated	-20	(-85, +320)
		Serious injury	-24	(-87, +355)
		Slight injury	-22	(-86, +332)
		Property damage only	+55	(-71, +736)
4	Yield	Fatal	-64	(-97, +416)
		Injury, severity not stated	-50	(-86, +86)
		Serious injury	-53	(-90, +114)
		Slight injury	-51	(-88, +102)
		Property damage only	-3	(-75, +273)
	Traffic signals	Fatal	-59	(-97, +273)
		Injury, severity not stated	-43	(-87, +157)
		Serious injury	-46	(-90, +177)
		Slight injury	-45	(-88, +166)
		Property damage only	+10	(76, +412)