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Problems in determining the optimal use of road safety measures

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ABSTRACT

This paper discusses some problems in determining the optimal use of road safety measures. The first of these problems is how best to define the baseline option, i.e. what will happen if no new safety measures are introduced. The second problem concerns choice of a method for selection of targets for intervention that ensures maximum safety benefits. The third problem is how to develop policy options to minimise the risk of indivisibilities and irreversible choices. The fourth problem is how to account for interaction effects between road safety measures when determining their optimal use. The fifth problem is how to obtain the best mix of short-term and long-term measures in a safety programme. The sixth problem is how fixed parameters for analysis, including the monetary valuation of road safety, influence the results of analyses. It is concluded that at it is at present not possible to determine the optimal use of road safety measures precisely. One may at best determine a range that is likely to contain the optimal use of a set of measures.

Key words: road safety measures; optimal use; economic analysis; cost-effectiveness

JEL: H41, H43, H51, I18, R41, R42

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1 INTRODUCTION

Public finances are under great pressure in many countries and it is more important than ever before for the public sector to spend money as efficiently as possible. There is therefore an interest in analyses aiming to determine the optimal use of policy instruments in many areas of public policy, including road safety policy. Previous analyses (Elvik 2001, 2003A) have found that current policy priorities for road safety are inefficient, i.e. road safety measures are not used optimally. An optimal use of road safety measures means that each measure is used to such an extent that its marginal benefits equal marginal costs. If used optimally, road safety measures will provide the largest possible surplus of benefits over costs.

It is, however, not possible to determine the optimal use of road safety measures very precisely. Both costs and benefits of road safety measures are imprecisely known (Elvik 2010A) and there are poorly understood interactions between these measures with respect to their effects on safety (Elvik 2009). At the current state of knowledge, a policy analysis can therefore only determine a range of safety outcomes which are likely to result from an optimal use of road safety measures. Improved knowledge may narrow this range, but it will never become zero.

This paper discusses some problems in determining the optimal use of road safety measures that have not been dealt with extensively in previous analyses. These problems include:

1. How can the baseline (reference option) for estimating the effects of road safety measures be established?
2. How can targets for intervention be optimally selected?

3. How can policy options be developed that minimise the risk of indivisibilities or irreversible decisions that are suboptimal?
4. How can interdependencies between measures be managed in a way that prevents suboptimal priorities from being set?
5. How can an optimal mix between long-term and short-term measures be determined?
6. How do fixed parameters for analysis (discount rate, etc.) influence the optimal use of road safety measures?

2 ESTABLISHING THE BASELINE (REFERENCE OPTION)

To estimate the effects of a road safety measure, or set of measures, one has to answer the following question: How is safety likely to develop if the measures are not introduced? Once this counterfactual condition has been described, changes in safety that will result from use of a set of road safety measures can be estimated. How best to model the expected development of road safety in the absence of the safety measures whose effects the analyst wants to estimate is an issue that has hardly received any attention in the literature. An interesting discussion of the issue, including a method which at least partly solves the problem is presented by Broughton and Knowles (2010). The method involves trying to estimate the contribution road safety measures has made to the past trend and then re-estimate the trend by removing the contribution made to it by road safety measures. Figures 1 and 2 illustrate this approach. Figure 1 is based on a recent Norwegian study of factors that have contributed to reducing the number of fatalities and seriously injured road users from 2000 to 2012 (Høye, Bjørnskau and Elvik 2014).

Figure 1 about here

Figure 1 identifies four main groups of factors that have contributed to the declining trend. The trend has been projected to 2024. This projection assumes that the factors that generated the declining trend from 2000 to 2012 will continue to do so at the same rate until 2024. Is such an assumption reasonable? Vehicles are likely to continue to become safer, but the safety systems that started to penetrate the market during 2000-2012 will mostly have reached full penetration before 2024. Unless new safety systems are developed, the contribution from safer vehicles will therefore become smaller and be close to zero by 2024. Road user behaviour became safer from 2000 to 2012, in particular in terms of lower speed and increased seat belt wearing. Seat belt wearing in Norway now exceeds 95 % and cannot be expected to continue to increase at the same rate as from 2000 to 2012. The tendency for speeds to become lower is also likely to flatten out.

The term demographic changes in Figure 1 refers to road user groups that experienced a particularly large decline in the number of fatalities and serious injuries from 2000 to 2012. Again, it is prudent not to assume that such changes will continue until 2024. The final factor listed in Figure 1, safer roads, should obviously not be included in any reference option, since one of the purposes of developing such an option is precisely to assess the need for further measures to make roads safer. Thus, it may be concluded that a conservative prediction for the term 2012-2024 should not include the effects of any of the factors that produced the declining trend during 2000-2012. Figure 2 presents such a prediction and contrasts it with the projection of the trend established during 2000-2012.

Figure 2 about here

It is seen that the two predictions differ clearly. As a basis for assessing the need for road safety measures, the counterfactual prediction is more relevant because it does not implicitly assume that past road safety measures will continue to be used and contribute to a declining trend.

3 OPTIMAL SELECTION OF TARGETS FOR INTERVENTION

The selection of targets for intervention, i.e. deciding where and when to introduce a certain road safety measure arises for all road safety measures that are used at the local level. This applies to all measures related to road design, traffic control and police enforcement. An optimal plan for selecting the locations for using a road safety measure specifies an order of selection that maximises the expected benefits of the safety measure. This means that, all else equal, a safety measure will first be implemented at the location where it produces the largest reduction of accidents or injuries, then at the location where the effect is second biggest, and so on.

It is difficult to develop a method ensuring that targets for intervention are selected this way. This principal problem is that selecting locations for safety treatments in practice takes place at the local level of government and is strongly influenced by site-specific characteristics that are difficult or impossible to include in a general model for optimal selection. Empirical studies (Elvik 2004) have found that sites selected for safety treatment tend to have high traffic volume. The number of accidents is strongly related to traffic volume; all else equal, sites with a high traffic volume would therefore be expected to have a high expected number of accidents. It has been found, however, that in Norway it is almost as common for sites with an abnormally low accident rate (accidents per million units of exposure) to be selected for treatment as it is for sites with an abnormally high accident rate.

Accident rates, as conventionally estimated, are subject to large random fluctuations. Any model for selecting sites for treatment should be based on good estimates of the long-term expected number of accidents, not a short-term count that to a very large extent reflects random variation. Selecting locations for treatment according to the empirical Bayes (Hauer 1997) estimate of the expected number of accidents is an attractive option. The empirical Bayes (EB) method for road safety estimation utilises two sources of data regarding safety to develop estimates that are site-specific and thus account for the site-specific characteristics that influence the selection for safety treatment. The two sources of data are:

1. A model-based estimate of the number of accidents expected to occur on a site with known values for all independent variables included in the accident prediction model.
2. The number of accidents recorded on a site during the same period as used to develop the accident prediction model.

The logic of the method is shown in Figure 3. A number of factors are entered into a multivariate accident prediction model and their relationship to accidents estimated.

Local risk factors cannot be included in such a model, but will influence the recorded number of accidents at a specific site.

Figure 3 about here

The empirical Bayes estimate of the expected number of accidents is a weighted average of the model-predicted number of accidents and the recorded number of accidents:

EB-estimate of the expected number of accidents = $E(\lambda|r) = \alpha \cdot \lambda + (1 - \alpha) \cdot r$

Here, λ is the model-predicted number of accidents and r is the recorded number of accidents. The weight, α, is defined as follows:

$$\text{Weight} = \alpha = \frac{1}{1+\frac{\lambda}{k}}$$

λ is the model-predicted number of accidents and k is the inverse value of the over-dispersion parameter of a negative binomial regression model. To illustrate the method, the following accident prediction model for junctions has been applied:

$$\text{Model} = Q_{maj}^{\beta_1} Q_{min}^{\beta_2} e^{(\alpha + (\beta_3 \cdot L) + (\beta_{4-8} \cdot SD_{50-90}))}$$

Q denotes entering volume. Subscript maj refers to the major road approaches, subscript min refers to the minor road approach. L is the number of legs. SD is a set of dummies for speed limit, one dummy for each speed limit. Coefficients estimated are denoted with the letters α (for the constant term) and β (for the predictor variables); e is the exponential function.

Figure 4 shows estimates of safety based on: (1) The recorded number of accidents; (2) The model-predicted number of accidents; (3) The EB-estimate of the number of accidents and (4) The model-based accident rate (from models containing traffic volume only) for 119 three-leg junctions with a speed limit of 50 km/h. The model presented above was used to develop model-based estimates.

Figure 4 about here

The recorded number of accidents takes on the values of 0, 1, 2 and 3. Most junctions recorded 0 accidents. This does not mean that the long-term-expected number of accidents in these junctions is 0. The EB-estimates are always located between the recorded number of accidents and the model predictions. It can be seen that some of the junctions that did not record any accidents have a higher long-term expected number of accidents than the junctions that recorded 1 accident. The EB-estimates of the number of accidents form a continuous variable displaying considerable variation. The accident rate, on the other hand, hardly varies and is thus unsuitable for identifying junctions with a special need for safety treatment.

4 AVOIDING INDIVISIBILITIES AND IRREVERSIBLE DECISIONS

Selecting sites for treatment on the road network can be approximated as a continuous function. There are, for example, several thousand junctions that can be selected for safety treatment and it is, in principle, possible to find the exact value of the expected number of accidents at which the marginal benefits of safety treatment equal the marginal costs. Other road safety measures are better modelled as binary choices. Legislation is a good example: you either make wearing bicycle helmets compulsory or you do not.

Legislation may create an indivisibility which is inconsistent with strict optimisation. A cost-benefit analysis of mandatory use of bicycle helmets (Høye et al. 2012) estimated benefits per child (present value) as 550 NOK (about 70 Euro in September 2013) and costs as 500 NOK, suggesting that a law requiring children to use bicycle helmets would be cost-effective. For adults, on the other hand, benefits per individual were estimated as NOK 735 and costs as NOK 1000. It is of course entirely possible to pass a law making the use of bicycle helmets compulsory for children only. However, this does not remove the indivisibility. Not all children have the same risk of bicycle accidents; some children are more at risk than others. To strictly optimise the use of bicycle helmets, only the children who are most at risk should be required to do so. However, since these children cannot be reliably identified, the only practical option is to require everybody to wear helmets.

Indivisibility and irreversibility may arise not only when legislation is passed, but also when new safety features become standard equipment on cars. Consider the case of making ISA (Intelligent Speed Adaptation) standard equipment on new cars. Cars in Norway average about 18 years when scrapped; as an approximation the time taken for the entire car fleet to turn over can therefore been set to 18 years. New cars are driven more than old cars; as cars get older the annual distance driven drops. As else equal, the benefits of ISA are therefore largest when a car is new and become smaller as the car gets older. A cost-benefit analysis (Elvik 2007) found that, while overall benefits clearly exceeded costs, marginal benefits dropped below marginal costs for cars aged 17 or 18 years, i.e. cars near the end of the normal service-life for cars in Norway. This is shown in Figure 5.

Figure 5 about here

It would be impractical to remove the ISA-system from the oldest cars. It is not even clear that it would be cost-effective to do so. In the first place, there are costs associated with removing the system. In the second place, cars not having ISA might attract drivers who enjoy driving at a high speed; this might in turn lead to an increase in accident involvement that would make it cost-effective to re-install the system.

Can indivisibility and irreversibility be avoided? It may not be possible to avoid these sources of suboptimality entirely. However, a strategy of encouraging voluntary adoption of a safety measure before it is made mandatory may reduce the risk of passing a law introducing an indivisibility. It has been found that there was propitious selection to ISA-trials in which drivers were offered rewards for not speeding (Elvik 2014), i.e. it was drivers with a low rate of speeding who volunteered for these trials. Similarly, it has been found that drivers wearing seat belts are less involved in accidents than drivers not wearing seat belts (Evans 1987, 1996). This implies that those who choose not to adopt a safety measure, such as seat belts or ISA, have a higher accident rate than the average for all drivers and will therefore benefit more from the safety systems than other drivers. Hence, if voluntary use of, for example, ISA can be brought up to a certain rate, it may no longer be the case that making it compulsory involves marginal benefits that are smaller than marginal costs for old cars, because these cars will then be driven by drivers with above-average accident rates.

5 INTERDEPENDENCIES BETWEEN MEASURES

The effect on safety of a given safety measure may depend on whether another safety measure has been introduced. This means that a safety measure that would be optimal to use at a certain level when another safety measure is not used, may no longer be optimal to use at all, or may have a different level of optimal use, if the other safety measure is used. These interactions and how best to model them are poorly known (Elvik 2009), but if they go unrecognised they may become a source of suboptimality. To illustrate the problem, a sensitivity analysis of the optimal use of road safety measures, discussed more in detail in section 7, will be used as example. The analysis (Elvik 2010B, 2011) was based on the mean number of traffic fatalities in Norway for 2006-2009, which was 236. For each road safety measure, its "first order" effect when used optimally was estimated. The term first-order effect denotes the effect of a measure when introduced by itself, i.e. as a stand-alone measure, not assuming that other measures will be used.

Denote the effect of a measure by E, and the proportion of accidents the measure does not prevent by R, the "residual" of the measure. Both E and R are stated as proportions and sum to 1. The combined effect of several measures is usually estimated as follows:

$$\text{Combined effect} = 1 - [(1 - E_1) \cdot (1 - E_2) \cdot (1 - E_3) \cdot \ldots \cdot (1 - E_n)]$$

Note that $(1 – E_i) = R_i$. This method for estimating the combined effects of road safety measures will be denoted as the method of common residuals. It assumes that the effects of a road safety measure is independent of the effects of any other road safety measure and remains, in percentage terms, unaltered when several road safety measures are combined.

It is clear that the assumption of independent effects is not always correct. Thus, in the analysis of optimal use of road safety measures in Norway, it was found that introducing more speed enforcement, ISA (Intelligent Speed Adaptation), and speed cameras were all optimal, as assessed in terms of their first-order effects. If, however, ISA is introduced, there is no longer any need for traditional speed enforcement or speed cameras. On the other hand, more speed enforcement may not eliminate the effects of ISA, since the police cannot do speed enforcement on all roads at all times. In a previous study (Elvik 2009), it was found that one way of accounting for interactions between measures was to estimate their combined effect by means of the "dominant common residuals method", which is specified as follows:

Dominant common residuals estimate = 1 - $(\prod_{i=1}^{n} R_i)^{R_{min}}$

The parenthesis is the product of the residuals. In the dominant common residuals method, this is raised to the power of minimum value of the residuals found in a set of measures. Thus, for three measures with residuals 0.7, 0.6 and 0.5, simple estimate of their combined effects is:

Combined effect (simple): $1 – (0.7 \cdot 0.6 \cdot 0.5) = 0.79$ (79% accident reduction)

The dominant residuals combined effect is:

Combined effect (dominant) = 1 – [$(0.7 \cdot 0.6 \cdot 0.5)^{0.5}$] = 1 – 0.46 = 0.54 (54 % accident reduction)

The choice of method for estimating combined effects may therefore have a large influence on results. The sum of first order effects of road safety measures used optimally in Norway is a fatality reduction of 164 (from a baseline of 236). Combined effects according to the simple common residuals method is a fatality reduction of 120. If the dominant common residuals method is applied, combined effects amount to a fatality reduction of 108. It is clear that the combined effect of the measures cannot be greater than the simple common residuals estimate (120) and may be smaller than the dominant common residuals estimate (108). Since the combined effects are invariably smaller than the sum of first-order effects, assessing optimal use in terms of first-order effects leads to an overestimate of the level of optimal use when several measures are combined in a programme.

6 MIX OF SHORT-TERM AND LONG-TERM MEASURES

The rule for priority setting in cost-benefit analysis is to select projects according to their net present value (Boardman et al. 2011, page 33-34). Boardman et al. (2011) explain that projects with different time frames are not directly comparable. To make them comparable, they suggest converting net present value to equivalent annual net benefit. This is done by dividing net present value with the annuity factor. To illustrate how such a conversion may influence priority setting between measures, three measures designed to reduce speeding will be used as example. The net present value of benefits (i.e. the present value of benefits minus the present value of costs) has been estimated to:

9786 million NOK for ISA on all vehicles.

1265 million NOK for section control.

738 million NOK for police enforcement.

Based on these values, installing ISA in all cars would appear to be the best option. Moreover, if that is implemented the other two measures will no longer be needed. However, the net present values refer to different time periods. In the case of ISA, it has been assumed that a complete turnover of the vehicle fleet takes 18 years; hence it will take 18 years for the full net benefits to be realised. Section control has been assumed to have a service life of 10 years. As far as conventional police enforcement is concerned, simultaneity of benefits and costs has been assumed. For this measure no discounting is involved and both benefits and costs apply to a period of one year.

Converting net present value this way gives an equivalent annual net benefit of 777 million NOK for ISA and 160 million NOK for section control. ISA thus appears to remain a better option than police enforcement, but only marginally so. However, as noted above, the benefits of ISA depend on annual driving distance, which tends to go down as a car gets older. It may therefore be more cost-effective to encourage the use of ISA for cars that are driven long annual distances, such as taxis or delivery vans. To help assign priorities between measures with different time frames, it is necessary to perform an analysis of their equivalent annual marginal net benefits. For ISA, this was done by dividing cars into nine groups with respect to annual average driving distance. The highest annual driving distance was assumed to be 40,000 kilometres; the lowest 2,000 kilometres. Accident involvement was assumed to depend on annual driving distance, but not be strictly proportional to it. The average annual expected number of accidents per car was set to 0.12 (based on insurance statistics). The mean annual number of accidents (all severities included) was assumed to range from 0.066 for cars driven 2,000 kilometres per year to 0.170 for cars driven 40,000 kilometres per year. For each group, the present value (18 years, 4.5 percent discount rate) of benefits and costs and the corresponding equivalent annual net benefits were estimated. The marginal equivalent annual net benefit of successively introducing ISA for cars with lower annual driving distance could then be obtained.

The procedure can be explained by reference to Table 1. Table 1 presents the assumptions made in order to estimate the equivalent annual marginal net benefits of introducing ISA. Please note that the assumptions made are not in all respects identical to those presented earlier in the paper regarding effects of ISA. These differences are unimportant, as the main purpose is to explain how measures with different time frames can be analysed to obtain a comparable basis for priority setting.

Table 1 about here

The first line of Table 1 presents data regarding cars driven 40,000 kilometres per year. It has been assumed that 25,000 cars in Norway are driven this distance every year (typically taxis or other commercial vehicles). For these cars, the net benefit of ISA (present value) has been estimated to be 265 million NOK. This corresponds to an equivalent annual benefit of 21 million NOK (the annuity factor is 12.593). Each line in Table 1 represents the marginal benefits and costs of ISA for cars listed on that line of the Table, i.e. it represent the effects of ISA in that particular group of cars.

It is now possible to compare the net benefits of ISA, police enforcement and section control. For police enforcement, as noted above, benefits and costs occur at the same time and no discounting is involved. Hence, net marginal benefits of increased police enforcement can be interpreted as equivalent annual marginal net benefit. Table 2 lists the marginal net benefits of increased police enforcement up to the point where marginal benefits equal marginal costs.

Table 2 about here

The marginal net benefits of increasing police enforcement are positive up to 3.5 times the current level of enforcement (250 percent increase). It is, however, not optimal to increase police enforcement to more than 3 times the current level. Beyond that, section control by means of speed cameras provides a larger equivalent annual marginal net benefit. Table 2 shows the annualised benefit of section control in two versions. The first version refers to the “first-order” effect of section control, i.e. the effect not taking into consideration interaction with other measures. The adjusted estimates account for the fact that police enforcement has been increased to 3 times the current level. This reduces the number of accidents section control can influence and this reduces marginal benefits. It is optimal to introduce section control on 15 kilometres of road with a high traffic volume. Beyond that, ISA becomes more cost-effective.

The numbers inserted in parenthesis in Table 2 indicates the priority that should be given to the various levels of use of the three measures. Note that the adjusted benefits of ISA account for the increase in police enforcement and the use of section control.

7 FIXED PARAMETERS FOR ANALYSIS – MONETARY VALUATION OF SAFETY

The results of cost-benefit analyses can be strongly influenced by fixed parameters for analysis. The values of important parameters, such as the discount rate, are often stated in official guidelines for cost-benefit analysis. These guidelines are periodically revised and new values of the parameters may then be proposed. Recently, a public commission in Norway reviewed important parameters for analysis and proposed changes in many of them, including (Norges offentlige utredninger 2012:16; see also Norges offentlige utredninger 1997:27):

1. The time horizon for analysis of infrastructure investments: Extending the period from 25 to 40 years was proposed.
2. The social discount rate: Reducing the risk-adjusted rate from 4.5 percent per annum to 4.0 percent per annum was proposed.
3. Real growth in monetary valuation of non-market goods: An annual real growth of 1.5 percent in the valuation of environmental goods and road safety was proposed.
4. Real growth in demand (traffic growth): Allowing for an annual traffic growth of 1.5 percent was proposed.

It is clear that the sum of these changes could have considerable impact on the results of cost-benefit analyses. An analysis of the benefits of converting to roundabouts the 119 junctions that were used as example in the section discussing selection for safety treatment was made. It was assumed (Elvik 2003B) that converting the junctions to roundabouts would reduce fatalities by 49 percent, serious injuries by 33 percent and slight injuries by 31 percent. These safety benefits were valued monetarily as 30.22 million NOK per prevented fatality, 10.59 million NOK per prevented serious injury and 0.61 million NOK per prevented slight injury (Veisten, Flügel and Elvik 2010). The 119 junctions were rank-ordered according to the empirical Bayes estimate of the number of accidents. The highest ranked junction was expected to have 0.241 injury accidents per year; the lowest ranked junction was expected to have 0.003 injury accidents per year. Average values were applied for the number of injured road users per injury accident and the distribution of injuries by injury severity. Figure 6 shows the present value of benefits for the highest ranked junction.

Figure 6 about here

Applying the current parameters for analysis (25 years; 4.5 percent discount rate; 0 percent growth in valuations; 0 percent traffic growth), the present value of benefits is estimated to 4.518 million NOK. When the recently proposed new values are used for all parameters, the present value of benefits is more than doubled and becomes 10.103 million NOK. This has major implications for the number of projects that will pass the cost-benefit test. Assuming (Elvik 2007) that, on average, it costs 5 million NOK to convert a three-leg junction to a roundabout, not a single junction would be converted when current parameters for analysis are used. The largest value of the benefits is 4.518 million NOK, less than the cost of conversion. When the proposed new values are used, benefits exceed costs in 18 junctions, which would justify a budget of 90 million NOK for converting junctions to roundabouts.

A logical next step is to analyse the sensitivity of the optimal use of road safety measures to the monetary valuation of road safety. The public commission quoted above (NOU 2012:16) recommended a valuation of 30 million NOK for the prevention of an accident fatality in Norway. However, both lower and higher estimates would be consistent with the research literature on valuation (Lindhjem, Navrud, Biasque and Braathen 2012). To test the sensitivity of the optimal use of road safety measures with respect to the monetary valuation of safety, values per prevented fatality of 15, 30 and 60 million NOK were applied. The value of preventing injuries was varied in proportion to the value of preventing a fatality.

For each measure, its optimal level of use in terms of first-order effects was determined by examining the functional relationship between costs and benefits. Figure 7 shows an example of this type of analysis. Costs are shown on the abscissa, benefits (in monetary terms) are shown on the left ordinate. Since each measure is assumed to be implemented in order of declining marginal benefits, the functions rise steeply close to the origin and then become flatter. Three functions are shown: one based on a low monetary valuation, one based on the recommended valuation and one based on a high monetary valuation.

Figure 7 about here

For each of these functions, the point at which the first derivative equals 1 has been determined. This is the point at which marginal benefits equal marginal costs. Note that for some measures, benefits not only include improved safety, but also savings in travel time or other benefits. In figure 7, the optimal level of use at the low monetary valuation equals 1450 million NOK, which would prevent 0.7 fatalities. The number of fatalities prevented is shown by the dashed function and plotted on the right ordinate. At the recommended monetary valuation, the optimal investment is 3180 million NOK, preventing 1.5 fatalities. If the high monetary valuation is adopted, optimal investment is 5480 million NOK, preventing 2.4 fatalities.

Similar analyses were made for 39 road safety measures. Their combined effects were then estimated by means of the dominant common residuals method, which gives the most conservative estimates of effect. The baseline number of fatalities was 236, the annual mean number for 2006-2009. The results are shown in Figure 8.

Figure 8 about here

It is seen that the results of analysis depend strongly on the monetary valuation adopted. The optimal number of fatalities is 157 at the lowest valuation, 103 at the highest. As noted above, all the values used can be defended by reference to valuation studies or syntheses of such studies. There are really no strong reasons for claiming that one of the monetary values is considerably better supported by research evidence than the others. This shows that it is an illusion to think that the optimal level of road safety can be determined very precisely. One can at best only determine a range, like the one shown in Figure 8.

It is also worth noting that the estimated combined effects of the measures are much smaller than the sum of their first-order effects. Thus, when forming part of a package of measures, each measure will contribute to a smaller reduction of the number of fatalities than when the measure is used alone. When the high monetary valuation is applied, the sum of first-order effects is a fatality reduction of 228. The combined effects is a fatality reduction of 149 according to the simple common residuals method and a fatality reduction of 133 according to the dominant common residuals method. However, the optimal use of each measure was determining according to its first order effects. It is clear that the optimal use may be at a much lower level when a measure forms part of a programme. Finding the exact optimal level is impossible and involves an endless regress. One might, to be sure, re-estimate the optimal level by adjusting it downwards for each measure by, for example, the ratio 133/228 (the ratio of combined effect to sum of first-order effects) as a first approximation. This would only re-create the problem at a different level, since the combined effects will always be smaller than the sum of first-order effects and the two will never converge.

8 DISCUSSION

There is no shortage of criticism of cost-benefit analysis (see, for example, Ackerman and Heinzerling 2004, Hauer 2011). It should in no way be regarded as a very precise instrument for policy analysis; all its results are uncertain. However, predicting the impacts of road safety measures is inherently difficult; the relevant question as far as cost-benefit analysis is concerned is whether predicting effects is more difficult as part of a cost-benefit analysis than it is if a different approach to policy analysis is taken.

The first problem discussed in this paper is fundamental, but has nevertheless hardly been a topic for research. This is the problem of how best to answer the following question: What is the best estimate of how road safety can be expected to develop if no new road safety measures are introduced? It is absolutely necessary to answer this question when developing a road safety programme. If the answer is that road safety can be expected to improve even if no new measures are introduced, a road safety programme may not be needed. If, on the other hand, the answer is that without new road safety measures, the historical trend for traffic fatalities to decline will reverse, a road safety programme is needed.

The question of how safety will develop without a safety programme is, in a sense, impossible to answer. Past development cannot serve as a guide; history does not produce both an actual development and a counterfactual development. But, one may object, is it not possible to estimate the counterfactual development by applying multivariate techniques to model changes over time in road safety? In principle, this is possible, but it is unlikely to entirely solve the problem. Many road safety measures are introduced gradually and steadily over time; the historical use of these measures does not have sufficient variation in time and/or space to be estimated statistically, but is likely to end up in the trend term. An alternative approach involving historical reconstruction was proposed in this paper, but any such reconstruction will be incomplete – there are no complete historical records of the use of all road safety measures – and its accuracy remains unknown.

Another issue where more research is needed concerns the combined effects on safety of several measures that form a programme. This is a topic where very little research exists. In principle, it is possible for measures to interact in a way that makes their benefits smaller than the costs if all measures are included in a programme, whereas benefits are greater than costs if only one, or maybe a few, of the measures are included in a programme. The guidance that at present can be given to policy analysts regarding how best to model interactions between road safety measures is incomplete.

As far as some of the other issues discussed in this paper are concerned, it is more a matter of improving the practice of cost-benefit analysis than of doing more research. It is inevitable that key parameters for analysis, such as the social discount rate, will be revised occasionally. However, since cost-benefit analyses often deals with long-term investments, it makes sense to assess how sensitive the results of analysis are to changes in key parameters, like the discount rate. Given the fact that there are so many sources of uncertainty in any cost-benefit analysis, sensitivity analysis should be part of any such analysis.

9 CONCLUSIONS

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

1. To define the basis for estimating the expected effects of road safety measures, it is necessary to predict how safety will develop if these measures are not introduced (the counterfactual). This is difficult, but it is suggested

that a workable procedure is to identify factors that have influenced past trends, in order to estimate a counterfactual trend, not influenced by past road safety measures.

2. Selection of targets for intervention, in particular locations on the road network where road safety measures will give maximum benefits, should be based on the empirical Bayes approach to road safety estimation.
3. Legislation requiring the use of a certain safety measures often involves indivisibility in the sense that the law is applied universally to heterogeneous groups of road users, for some of whom the benefits of the law are likely to be smaller than the costs. To minimise the risk of passing such laws, policy makers should initially encourage a voluntary use of the safety measure; this will normally induce propitious selection, so that by the time voluntary use of a safety measure is widespread, the remaining non-users are likely to have a sufficiently high risk of accident involvement to avoid indivisibility.
4. The current basis for modelling interdependencies between road safety measures, meaning that the effect of a measure depends on whether another road safety measure is used or not, is very weak. It is therefore recommended to analyse the marginal benefits of each road safety measures in detail and systematically vary assumptions regarding the use of other measures.
5. Measures with different time frames should be made comparable by converting net benefits to equivalent annual benefits. These converted benefits should then form the basis for a comparison of the marginal benefits of various measures.

6. A number of fixed parameters (time horizon, discount rate, etc.) can greatly influence the results of cost-benefit analyses. While it is appropriate that the values of these parameters may change periodically, it should be recognised that they are uncertain and a sensitivity analysis of the parameters should be part of any cost-benefit analysis. This also applies to the monetary valuation of road safety.

ACKNOWLEDGEMENTS

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LIST OF FIGURES AND TABLES

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Sensitivity of the optimal provision of road safety to its monetary valuation

Table 1:

Costs and benefits of ISA for nine groups of cars – conversion of net benefits to equivalent annual net benefits

Table 2:

Comparative analysis of annualised marginal net benefits of three measures intended to curb speeding

Figure 1:

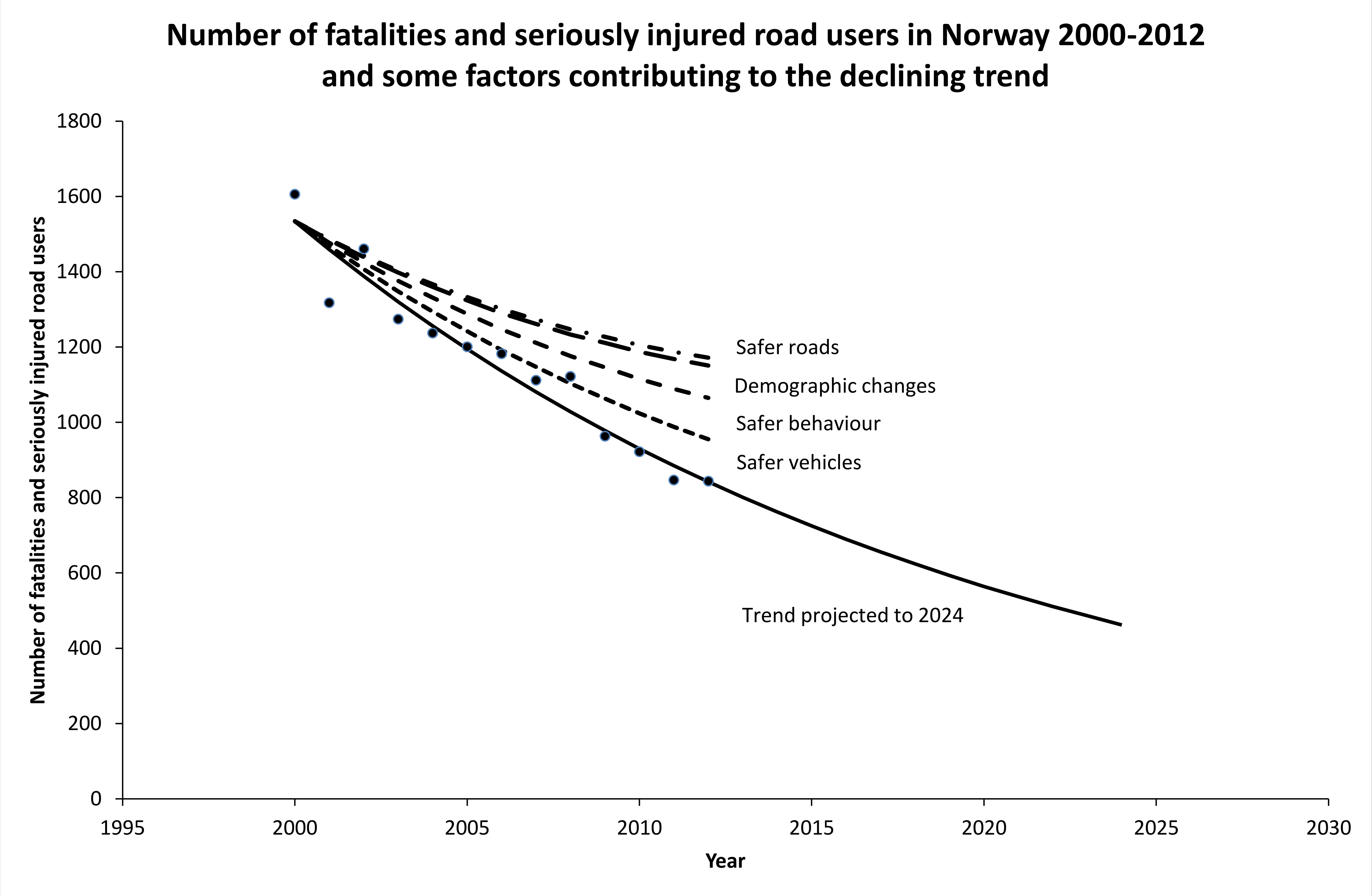
Number of fatalities and seriously injured road users in Norway 2000-2012 and some factors contributing to the declining trend
1800
1600
1400
1200
1000
800
600
400
200
0
Number of fatalities and seriously injured road users
1995
2000
2005
2010
2015
2020
2025
2030
Year
Safer roads
Demographic changes
Safer behaviour
Safer vehicles
Trend projected to 2024

Figure 2:

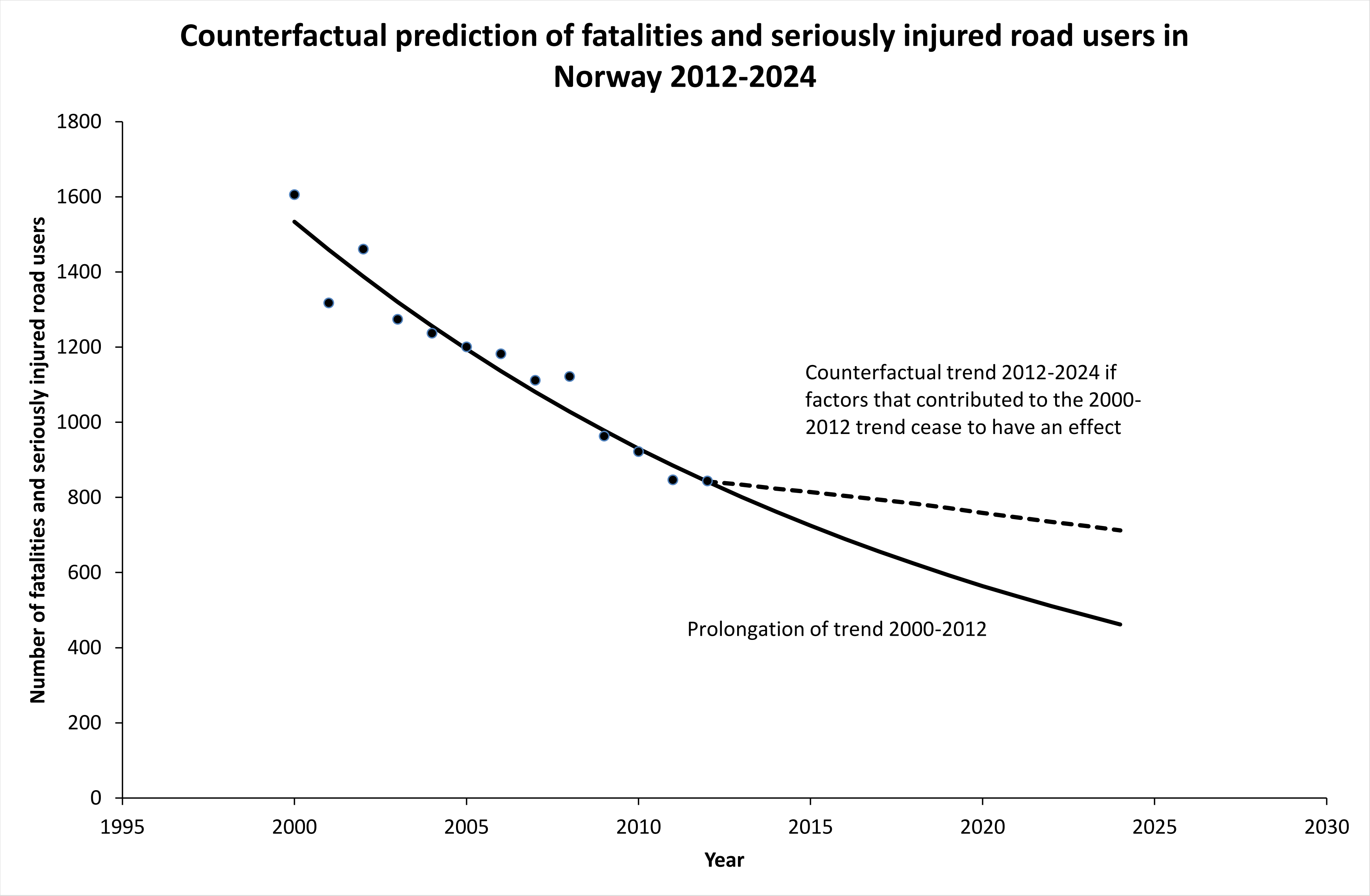
Counterfactual prediction of fatalities and seriously injured road users in Norway 2012-2024
Number of fatalities and seriously injured road users
1800
1600
1400
1200
1000
800
600
400
200
0
1995
2000
2005
2010
2015
2020
2025
2030
Year
Counterfactual trend 2012-2024 if factors that contributed to the 2000-2012 trend cease to have an effect
Prolongation of trend 2000-2012

Figure 3:

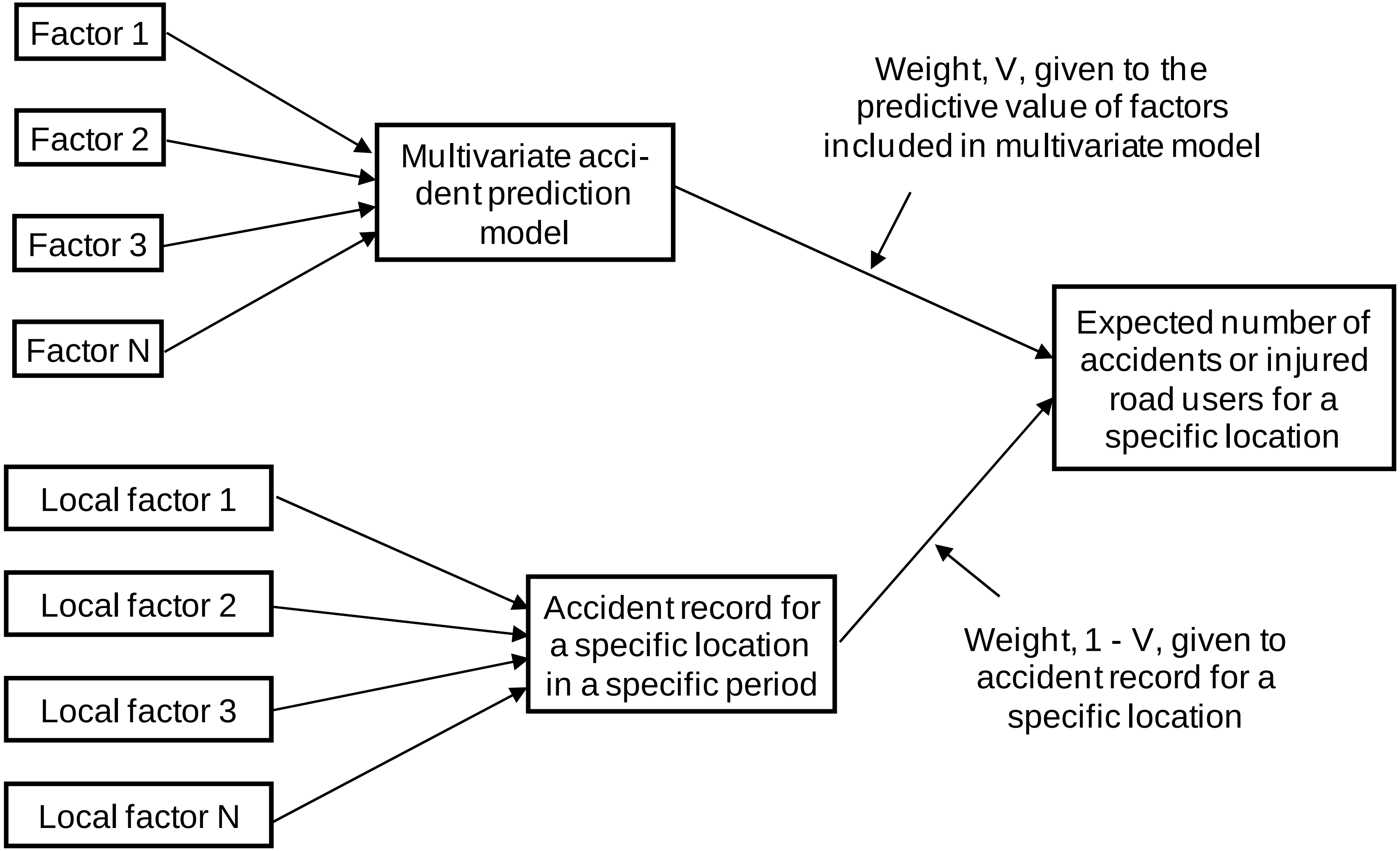
Factor 1
Factor 2
Factor 3
Factor N
Multivariate accident prediction model
Weight, V, given to the predictive value of factors included in multivariate model
Expected number of accidents or injured road users for a specific location
Local factor 1
Local factor 2
Local factor 3
Local factor N
Accident record for a specific location in a specific period
Weight, 1 - V, given to accident record for a specific location

Figure 4:

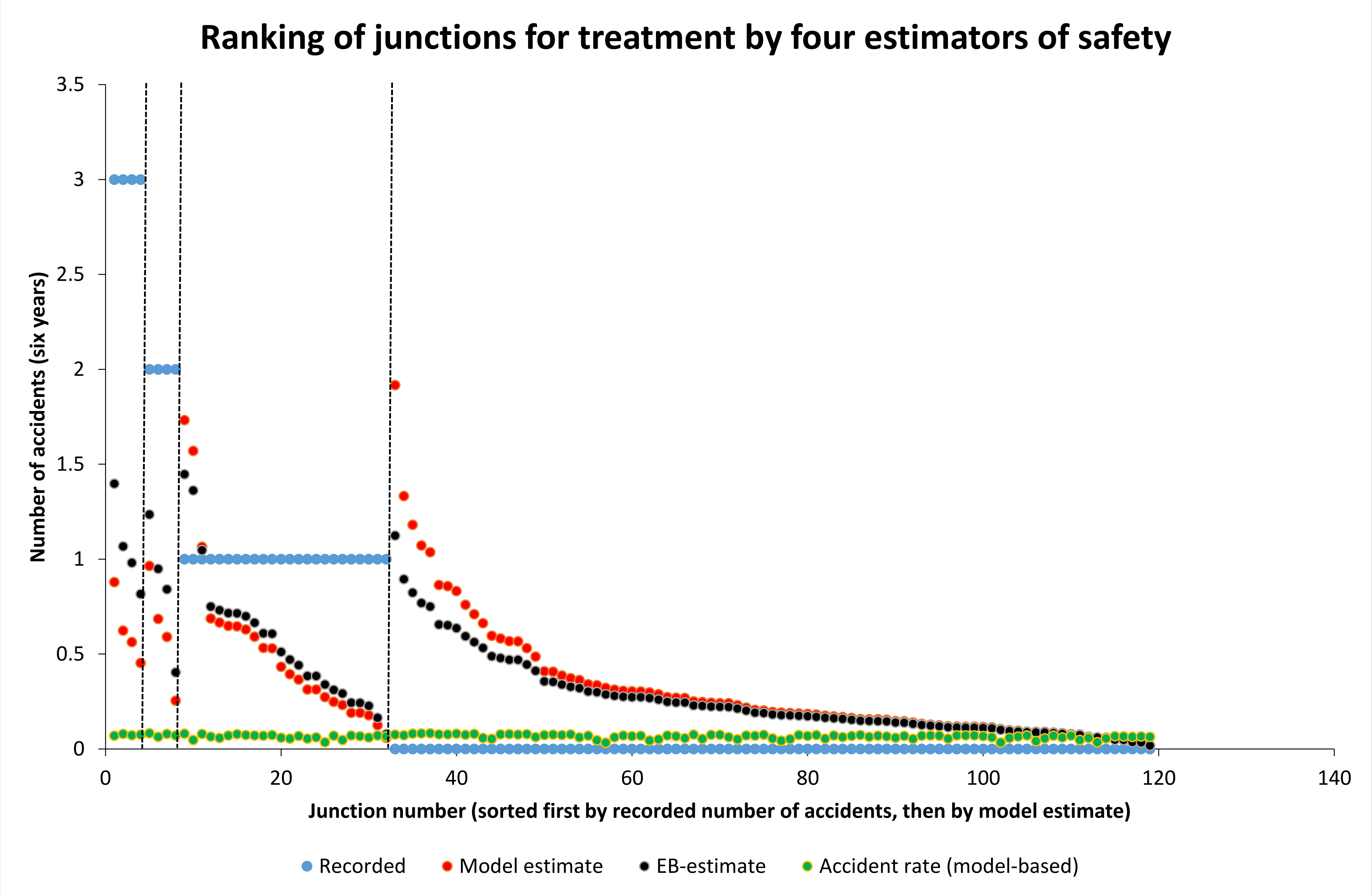
Ranking of junctions for treatment by four estimators of safety
Number of accidents (six years)
3.5
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
Junction number (sorted first by recorded number of accidents, then by model estimate)
● Recorded
● Model estimate
● EB-estimate
● Accident rate (model-based)

Figure 5:

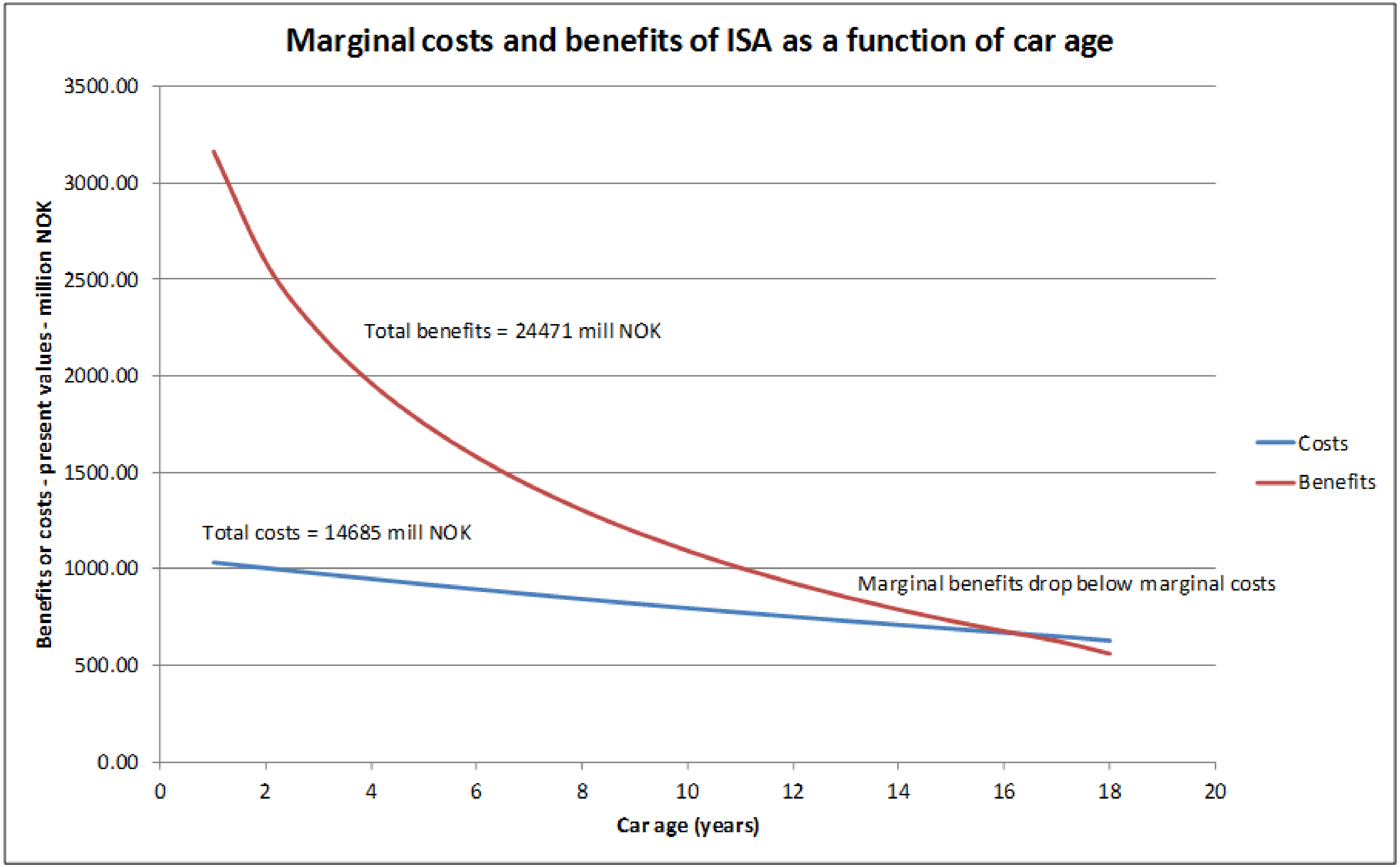
Marginal costs and benefits of ISA as a function of car age
Benefits or costs - present values - million NOK
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
0
2
4
6
8
10
12
14
16
18
20
Car age (years)
Total benefits = 24471 mill NOK
Total costs = 14685 mill NOK
Marginal benefits drop below marginal costs
Costs
Benefits

Figure 6:

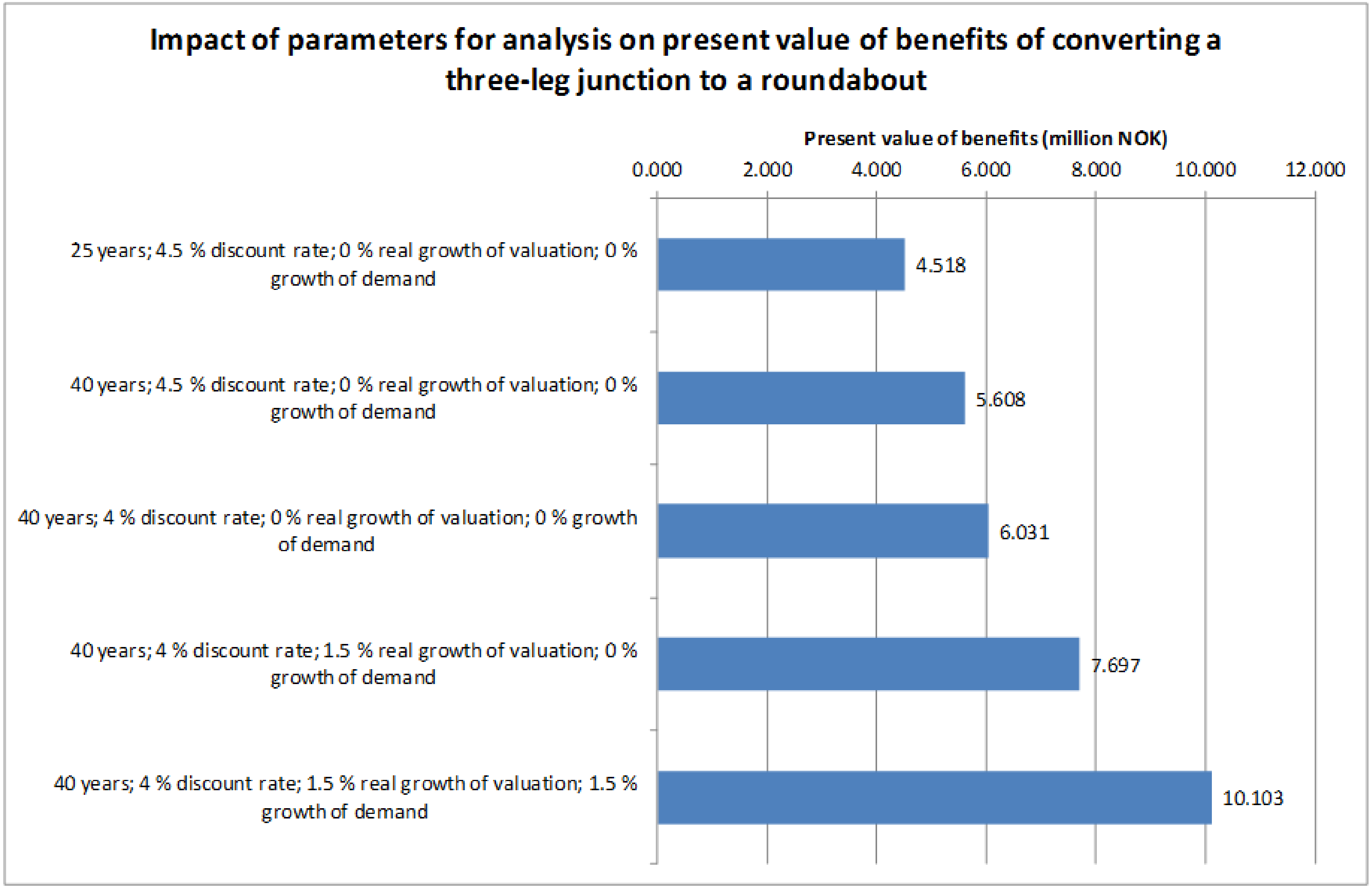
Impact of parameters for analysis on present value of benefits of converting a three-leg junction to a roundabout
Present value of benefits (million NOK)
0.000
2.000
4.000
6.000
8.000
10.000
12.000
25 years; 4.5 % discount rate; 0 % real growth of valuation; 0 % growth of demand
40 years; 4.5 % discount rate; 0 % real growth of valuation; 0 % growth of demand
40 years; 4 % discount rate; 0 % real growth of valuation; 0 % growth of demand
40 years; 4 % discount rate; 1.5 % real growth of valuation; 0 % growth of demand
40 years; 4 % discount rate; 1.5 % real growth of valuation; 1.5 % growth of demand
4.518
5.608
6.031
7.697
10.103

Figure 7:

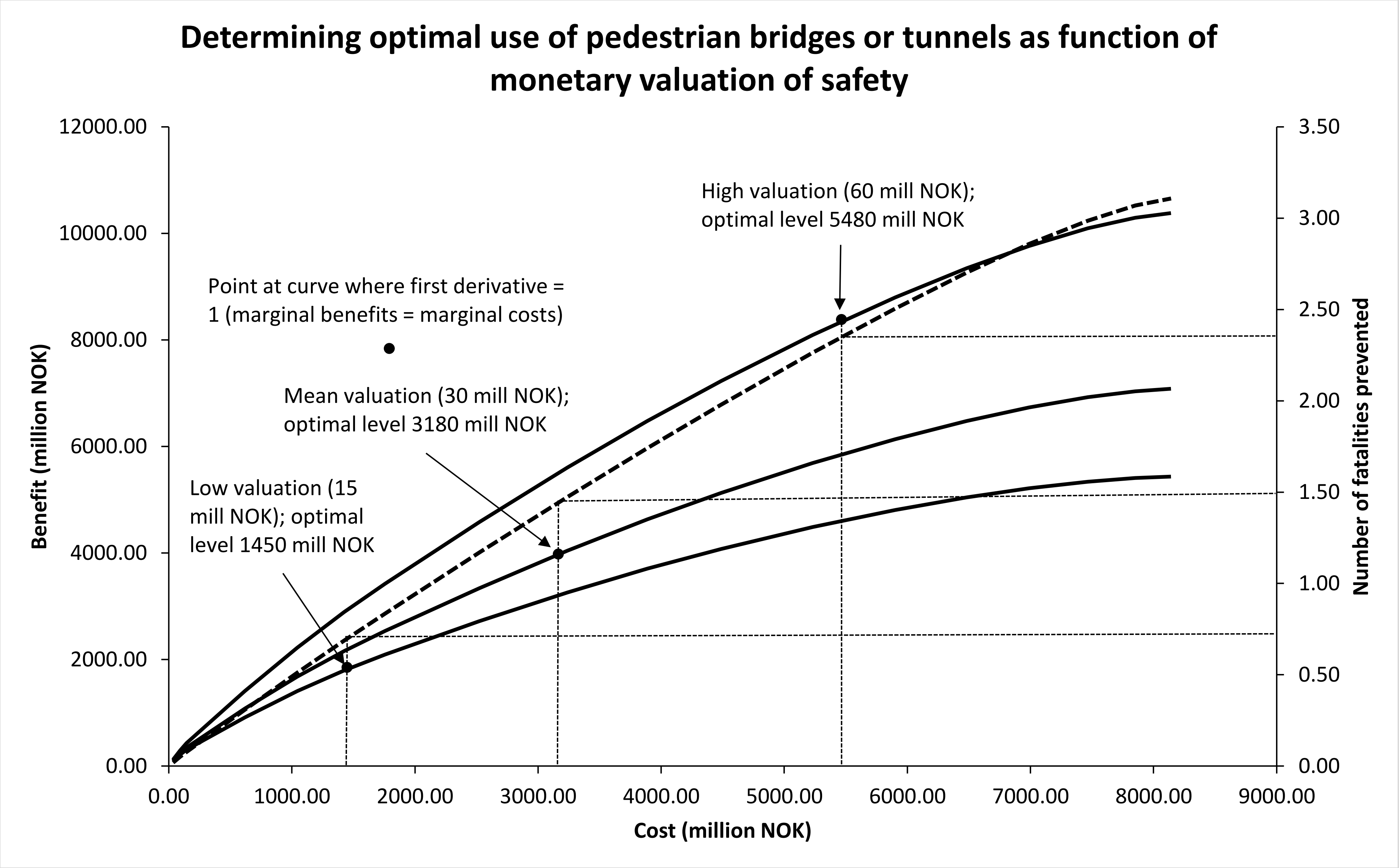
Determining optimal use of pedestrian bridges or tunnels as function of monetary valuation of safety
Benefit (million NOK)
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
Number of fatalities prevented
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Cost (million NOK)
0.00
1000.00
2000.00
3000.00
4000.00
5000.00
6000.00
7000.00
8000.00
9000.00
High valuation (60 mill NOK); optimal level 5480 mill NOK
Point at curve where first derivative = 1 (marginal benefits = marginal costs)
●
Mean valuation (30 mill NOK); optimal level 3180 mill NOK
Low valuation (15 mill NOK); optimal level 1450 mill NOK

Figure 8:

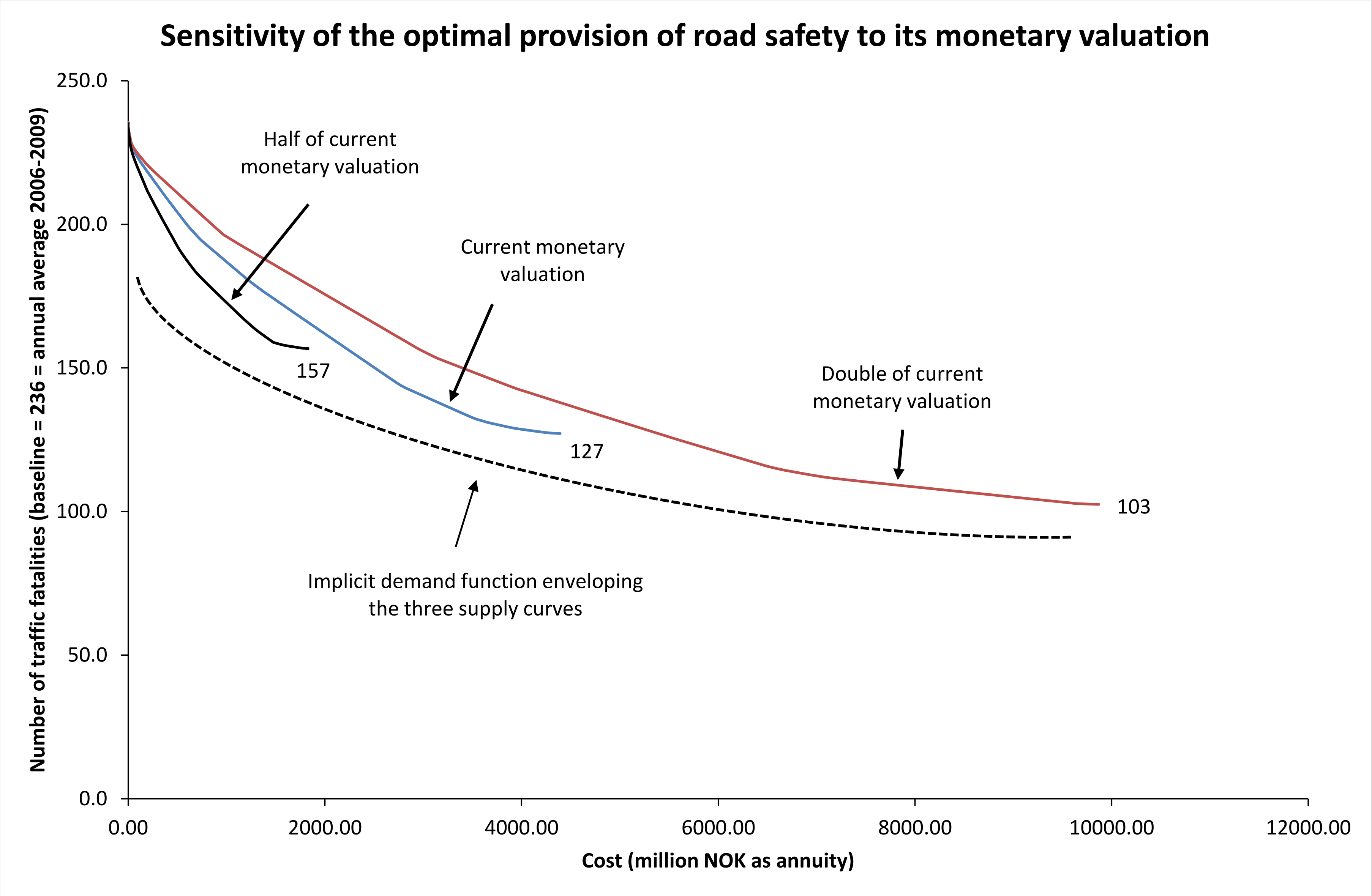
Sensitivity of the optimal provision of road safety to its monetary valuation
Number of traffic fatalities (baseline = 236 = annual average 2006-2009)
250.0
200.0
150.0
100.0
50.0
0.0
0.00
2000.00
4000.00
6000.00
8000.00
10000.00
12000.00
Cost (million NOK as annuity)
Half of current monetary valuation
157
Current monetary valuation
127
Double of current monetary valuation
103
Implicit demand function enveloping the three supply curves

Table 1:

Kilometres per car per year	Number of cars (rounded)	Total kilometres (million)	Accidents per car per year	Total number of accidents	Benefits of ISA (present values)	Costs of ISA (present values)	Net benefits of ISA (present values)	Equivalent annual marginal net benefits of ISA	Benefit-cost ratio (based on present values)
40000	25000	1000	0.170	4300	421.5	156.5	265.0	21.0	2.69
35000	50000	1750	0.163	8200	803.8	313.0	490.9	39.0	2.57
30000	105000	3150	0.155	16500	1617.5	657.2	960.2	76.3	2.46
25000	210000	5250	0.147	31000	3038.9	1314.5	1724.4	136.9	2.31
20000	560000	11200	0.137	77000	7548.2	3505.2	4042.9	321.0	2.15
14000	990000	13860	0.122	121250	11885.9	6196.7	5689.2	451.8	1.92
9000	560000	5040	0.106	60000	5881.7	3505.2	2376.5	188.7	1.68
5000	218000	1090	0.088	20000	1960.6	1364.5	596.0	47.3	1.44
2000	105000	210	0.066	6800	666.6	657.2	9.4	0.7	1.01
Total	2823000	42550	0.122	345050	33824.6	17670.0	16154.6		1.91

Table 2:

Police enforcement		Section control by means of speed cameras			Intelligent speed adaptation (ISA)		
Extent of use of measure	**Equivalent annual marginal net benefit (million NOK)**	**Extent of use of measure**	**Equivalent annual marginal net benefit (million NOK)**	**Adjusted equivalent annual marginal net benefit (million NOK)**	**Extent of use of measure**	**Equivalent annual marginal net benefit (million NOK)**	**Adjusted equivalent annual marginal net benefits (million NOK)**
50 % increase	***444 (1)***	First 15 km of road	38	***35 (4)***	Cars 40,000 km/year	21	***19 (5)***
100 % increase	***187(2)***	Next 10 km	18	16	Cars 35,000 km/year	39	***35 (6)***
200 % increase	***108(3)***	Next 10 km	15	14	Cars 30,000 km/year	76	***69 (7)***
250 % increase	1	Next 10 km	12	11	Cars 25,000 km/year	137	***123 (8)***
		Next 15 km	12	11	Cars 20,000 km/year	285	***285 (9)***
					Cars 14,000 km/year	395	***395 (10)***