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Can injury prevention efforts go too far? Reflections on some possible implications of Vision Zero for road accident fatalities

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Abstract

The Swedish National Road Administration has launched a long term vision of a road transport system in which nobody is killed or sustains an injury resulting in permanent impairment (Vision Zero). This paper examines some possible implications of Vision Zero for traffic fatalities. The main points of the paper can be summarised as follows: An objective of eliminating traffic deaths can be interpreted as an application of a general principle of minimising mortality. Minimising overall mortality implies that a survival lottery must be introduced, at any rate as long as there is a shortage of organs for transplants. A survival lottery is a scheme in which people are drawn at random to sacrifice their life for the benefit of others. An objective of eliminating a certain cause of death, like traffic accidents, may be so expensive to realise that there is so much less resources available to control other causes of death that general mortality increases. Several analyses of the relationship between income per capita and general mortality based on Norwegian data document a negative relationship between income and mortality. The loss of income that induces an additional statistical death, due to economic inefficiency, is estimated to between 25 and 317 million NOK (3.8–47.5 million US dollars). These estimates are in line with those of most previous studies. No study of the relationship between income and mortality fully satisfies commonly used criteria of causality. However, the balance of evidence suggests that the relationship between income and mortality is a causal one. A hypothetical programme designed to implement Vision Zero for traffic fatalities was developed and its effects on the number of fatalities estimated. Implementing the whole programme could reduce the number of traffic deaths in Norway from about 300 per year to about 90 per year. Applying the lowest estimate of the income loss that induces an additional death (25 million NOK), it was estimated that implementing the entire hypothetical Vision Zero programme would increase general mortality by about 1355. This would lead to a net increase of about 1145 deaths per year (1355 minus 210 prevented traffic deaths). The analyses presented in this paper show that the possibility cannot be ruled out that a massive effort to eliminate traffic deaths would be counterproductive in terms of overall mortality. This possibility must be regarded as a moral dilemma by advocates of Vision Zero, who have invoked the ethical principle that 'one must always do everything in one's power to prevent death or serious injury' to justify the vision.

Keywords: Vision Zero; Traffic deaths; Survival lottery; Mortality; Moral dilemma

1. Introduction

The current number of people killed in road accidents is regarded as unacceptably high in most motorised countries. Several countries have set long-term quantified targets, aiming at a substantial reduction in the number of road accident fatalities (OECD, 1994). The Swedish National Road Administration has launched a long-term vision of a road traffic system in which nobody is killed or sustains an injury resulting in lasting impairment. This long-term target is known as Vision Zero (Tingvall, 1997; Vägverket, 1997a,b). According to the Swedish National Road Administration, Vision Zero involves an entirely new way of looking at road safety and a new set of principles for designing and managing the road transport system. The emphasis is shifted away from enhancing the ability of road users to cope with an imperfect system, towards designing a system in which the system designers guarantee road users who comply with the basic regulations of the

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system that they will never sustain a fatal or serious injury. It is recognised that preventing all accidents is unrealistic. The aim is to control the energy released in accidents in a way that prevents deaths and injuries leading to permanent disability from occurring.

Most people will probably find this objective highly laudable. Road accidents involve a tremendous waste of human talent and welfare. However, despite an apparently widespread agreement that the present level of road accidents is unacceptable, no country has taken drastic action to reduce the number of road accident fatalities. The growth in motor travel is allowed to go on. The freedom of road users to choose their mode of transport is not infringed. Mean speeds have been increasing for a long time. Widespread violations of road traffic law are tolerated. Could the reason for this be a perception that the price of eliminating traffic fatalities is too high? This paper presents an analysis of some possible implications of Vision Zero for traffic fatalities, based on the ethical principles underlying this vision. The basic question guiding the analysis is whether injury prevention efforts can go too far, not according to economic criteria of efficiency, but according to the ethical principles on which Vision Zero is based.

2. Vision Zero for road accident fatalities

Vision Zero explicitly rejects the use of cost-benefit analysis to guide priority setting in road safety policy. Tingvall (1997) p. 56 states that: 'If a new road, new car design, new rule etc., is judged as having the potential to save human life, then the opportunity must always be taken, provided that no other more cost-effective action would produce the same safety benefit.' The notion that saving lives has to be traded off against other objectives is explicitly rejected in the first ethical principle of Vision Zero:

2.1. Ethical principle 1: maximising life saving. One must always do everything in one's power to prevent death or serious injury

In justifying this principle, Tingvall states that: 'It goes without saying that human life cannot be exchanged for some gain.' This is obviously true in the literal sense of the term exchange, but Vision Zero explicitly rules out any formal trade off whatsoever of safety against other objectives. Thus, ethical principle 3 states:

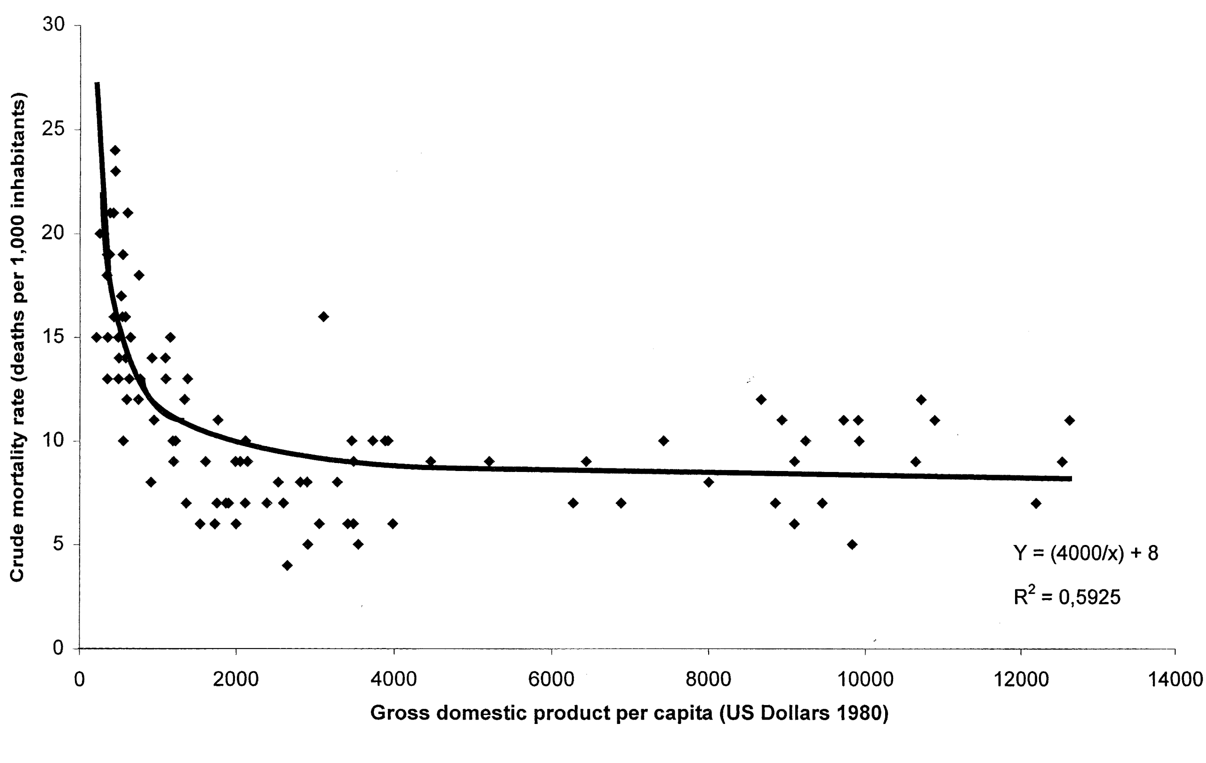

Fig. 1. Relationship between income (gross domestic product per capita) and crude mortality rate (death per 1000 inhabitants) for 101 countries.

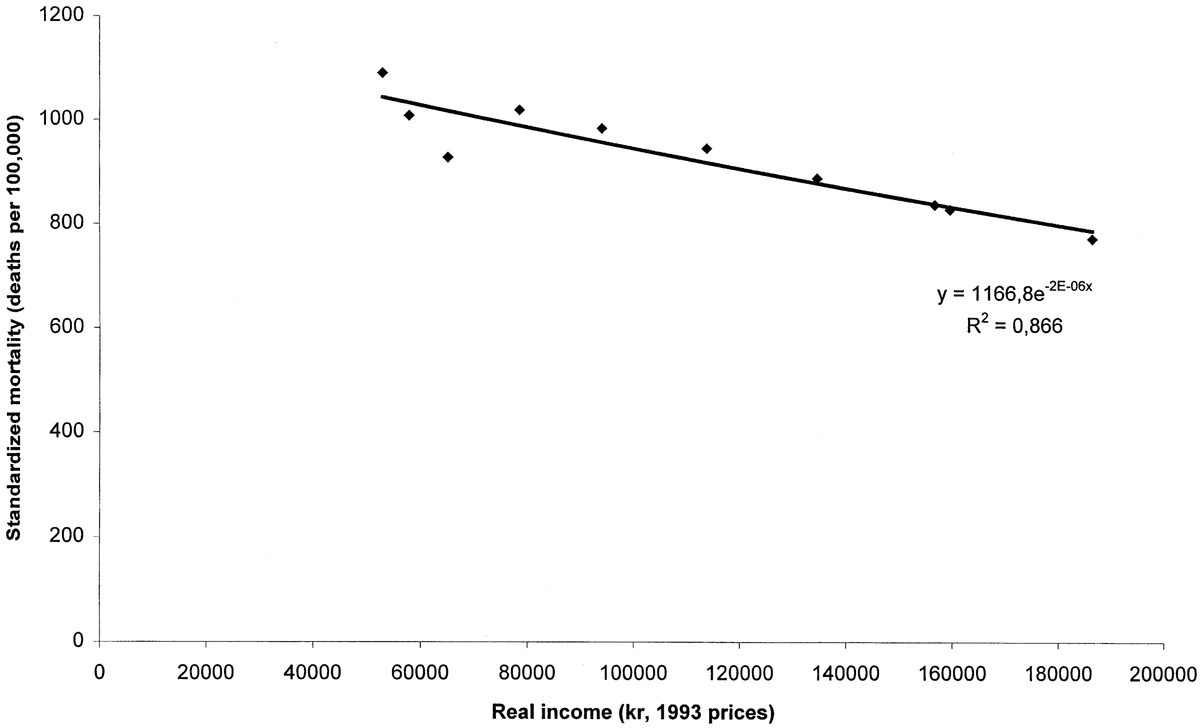

Fig. 2. Relationship between income (gross domestic product per capita in fixed prices) and standardised mortality rate (death per 1000 inhabitants standardised by age and sex) in Norway for ten 5 year periods (1946–1995).

2.2. Ethical principle 3: best solution should always be chosen. The best-known solution must always be applied

This ethical principle establishes a lexicographic (that is unconditional) preference of always choosing the technically best solution to a problem, even if that solution is more expensive than other solutions.

The ethical principles of Vision Zero not only reject the use of cost-benefit analysis as a way of making rational choices between competing objectives; these principles reject any compromise between safety and other objectives altogether. By thus establishing a lexicographic preference for safety, Vision Zero may run into inconsistencies its proponents may not have considered. Two of these possible inconsistencies are discussed in the next section.

3. Two possible implications of Vision Zero

In general, a lexicographic preference for life saving, irrespective of the cause of death, implies the need to set up a survival lottery. This was first recognised by Harris (1975), who introduced the idea of a survival lottery. Harris asks us to imagine that transplantation technology has been perfected. There are two patients awaiting transplantation in a hospital. Organs are in short supply and both patients will die if a transplant is not performed. By killing a healthy person, both patients can be supplied with the organs they need and two lives saved at the expense of one.

Harris notes that nearly all moral philosophers think it is morally wrong to kill, even if by doing so we could save life. He therefore introduces the idea of a survival lottery, in which every individual faces a certain probability of being drawn to sacrifice his or her life for the benefit of others. He argues that although we may find such a scheme repulsive, it is difficult to give compelling arguments against it based on moral philosophy. The introduction of a survival lottery would reduce the number of untimely deaths and thus contribute to the objective of maximising life saving. Nevertheless, most people are likely to reject the idea of a survival lottery. Harris conjectures that the rejection of a survival lottery is based on widely held moral intuitions. Hence, introducing such a lottery would be inconsistent with the notion of reflective equilibrium in moral theory, introduced by Rawls (1971). Reflective equilibrium is a mental state in which, upon careful reflection, we regard a set of moral principles as more consistent with our moral intuitions than any other set of moral principles. If the use of a survival lottery is inconsistent with our moral intuitions, it follows that maximising life saving cannot be regarded as a basic moral principle. Indirectly, the studies of Kunreuther (1982) and Nord et al. (1995) confirm that most people do not regard maximising the number of lives saved as a principle that is lexicographically prior to all other considerations in setting priorities among life saving activities. According to a recent medical paper (Lien et al., 1998), there were 150 people on waiting lists for transplants in Norway at the end of 1996. Shortage of organs result in a death rate of about 20–30% among those on waiting lists.

A survival lottery is implied by an objective of maximising life saving in general. An objective of eliminating a specific cause of death may, depending on how expensive it is to accomplish such a target, imply an increase in general mortality that may offset the reduction in mortality obtained by eliminating the target cause of death. This may occur because the mortality rate is negatively related to income. If expenditures devoted to the elimination of a specific cause of death grow without bound, the reduction in income (i.e. the amount of resources available to control other causes of death) may at some point be large enough to cause an increase in general mortality which more than offsets the elimination of the target cause of death.

A large number of studies evaluating the relationship between income, defined broadly speaking as gross national product per capita, and mortality have been reported in recent years (Keeney, 1990; Chapman and Hariharan 1994; Keeney 1994; Lutter and Morrall 1994; Smith et al., 1994; Viscusi, 1994a,b; Viscusi and Zeckhauser 1994; Keeney 1997). Most of these studies estimate the income loss that induces an additional statistical death. Most studies interpret the relationship between income and mortality as causal, although this interpretation is controversial. This paper will not try to settle the discussion about the causality of the relationship between income and mortality. It proceeds on the assumption that the statistical relationship between income and mortality rate is: (1) real, that is not attributable to measurement errors in the variables, sampling error or other statistical artifacts; (2) possibly causal, although a final conclusion with respect to causality must rest on a more rigorous analysis than the one presented in this paper.

4. Evaluation of income–mortality relationship in Norway

In order to assess the possible implications of Vision Zero for general mortality, the relationship between income and general mortality in Norway has been evaluated. The objective of this evaluation is to estimate the size of the income loss that induces an additional statistical death. Several data sets have been used to estimate the relationship between income and general mortality in Norway. In most data sets, income is measured as the gross national product per capita. Mortality is affected by a large number of variables, of which the most important are age, sex, life style (including habits with respect to eating, smoking and alcohol consumption) and availability of medical care.

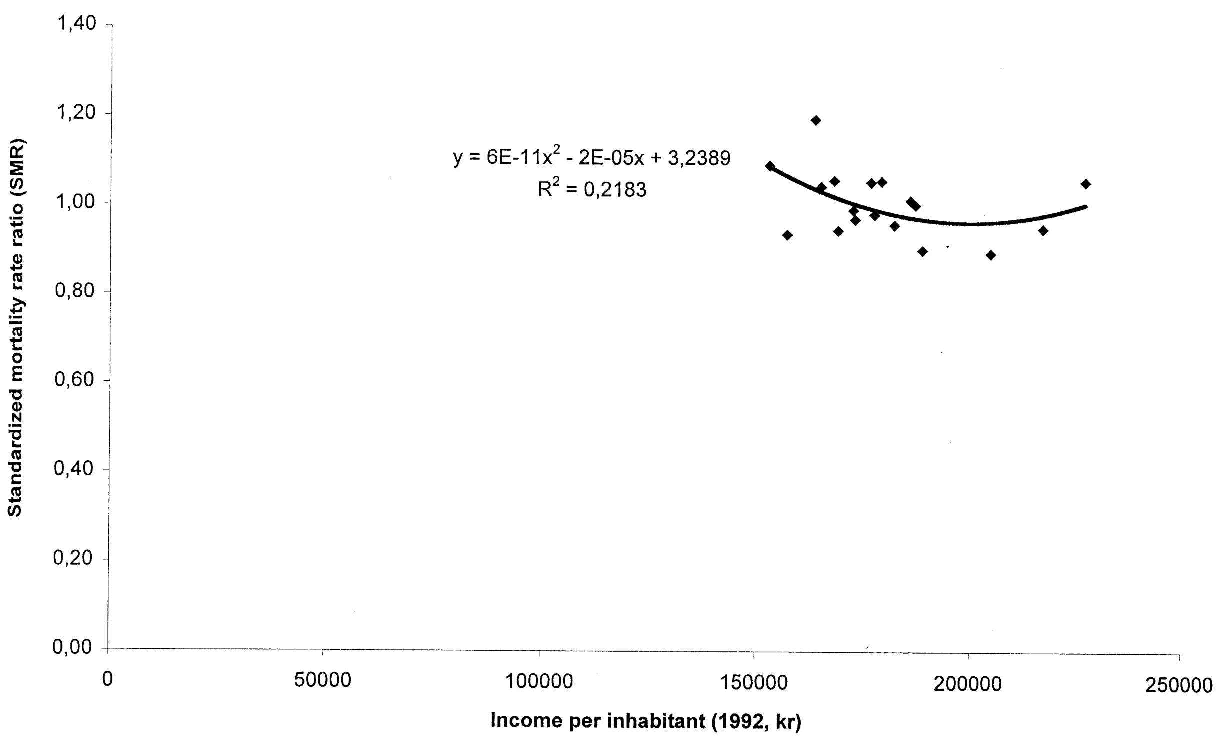

Fig. 3. Relationship between wage income per employed person and standardised mortality rate ratio (standardised by age) for 19 counties in Norway in 1992.

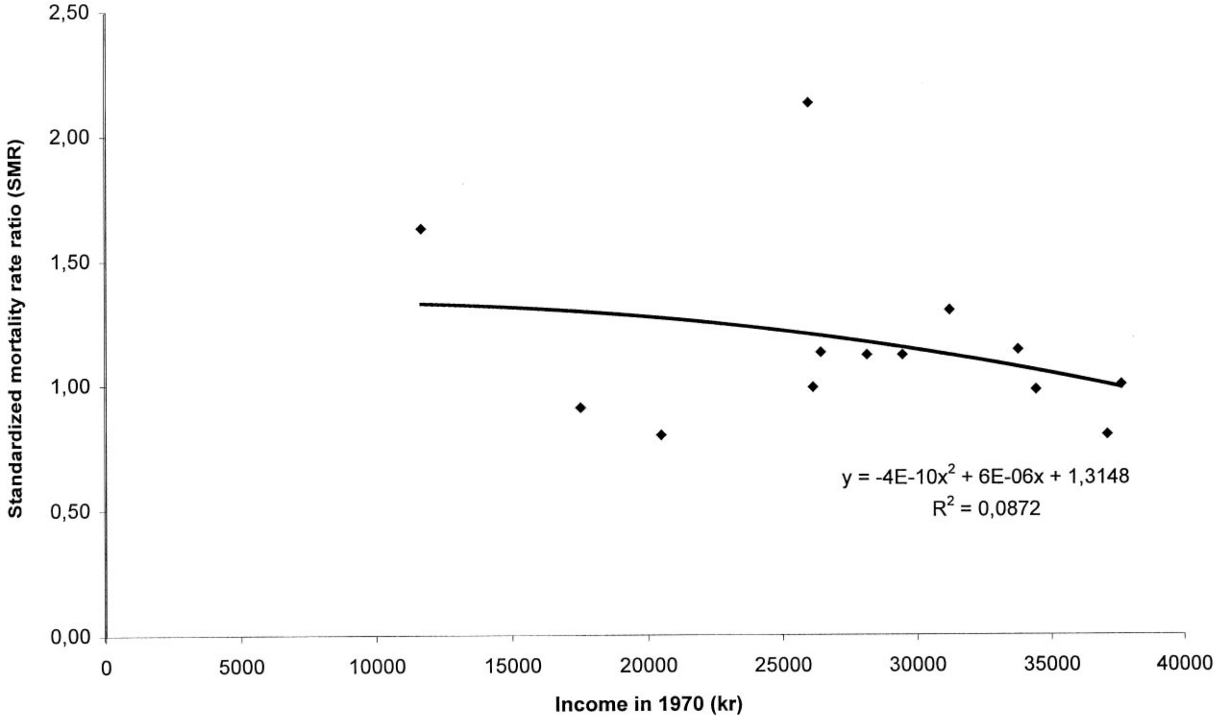

Fig. 4. Relationship between mean income per person in 1970 and standardised mortality rate ratio (restricted to men between 20 and 69 years) for the years 1970–1980 for 13 occupations in Norway.

Whenever possible, standardised mortality rates, which have been adjusted to remove the effects of at least some of these confounding variables, have been used in estimating the relationship between income and mortality.

Functions were fitted to the various data sets in order to summarise the relationship between income and mortality. The following functional forms were tested in all data sets and the best fitting function selected:

Linear: $Y = \alpha + \beta x$

Logarithmic: $Y = \alpha + \beta \ln(x)$

Exponential: $Y = \alpha \exp^{\beta x}$

Geometric: $Y = \alpha x^{\beta}$

Polynomial: $Y = \alpha x^2 + \beta x + \lambda$

Hyperbolic: $Y = \alpha / x + \beta$

In which Y is mortality, x is income and α, β and λ are parameters to be estimated. The fit of the various functions was assessed in terms of the squared correlation coefficient (Pearson's r). The results of the analyses are presented in Figs. 1–5.

Fig. 1 shows the relationship between gross national product per capita in 1980 US Dollars (adjusted to purchasing power parity) and crude mortality rate for 101 countries. The data are taken from Lutter and Morrall (1994). A hyperbolic function best fits these data. It is notable, however, that the residuals are not quite symmetrically distributed around the fitted curve. Smith et al. (1994) have criticised Lutter and Morralls analysis. Their criticism will be discussed later.

Fig. 2 shows the relationship between the gross national product per capita of Norway, measured in fixed 1993-prices and mortality, adjusted for age and sex, during ten 5 year periods from 1946 to 1995 (1946–1950, 1951–1955, etc.). An exponential function fits the relationship very well. General mortality in Norway has declined by about 20% during the last 50 years, while real income per capita has more than trebled (Statistisk sentralbyrå, 1994).

Fig. 3 shows the relationship between wage income per employed person and standardised mortality rate ratio for 19 counties in Norway in 1992 (Statistisk sentralbyrå, 1996, 1997). For each county, an expected mortality rate was estimated on the basis of the age distribution of the population in that county and age specific national mortality rates. The standardised mortality rate ratio was defined as the ratio of actual mortality rate to expected mortality rate in each county. Fig. 3 shows that there is only a weak relationship between income and standardised mortality rate ratio in Norwegian counties. A second order polynomial best fits the data, but explains only about 22% of the variance in mortality. Moreover, the slope of this polynomial is negative for low income and positive for high income, implying that an increase in income beyond a certain point is associated with increased mortality.

Fig. 4 shows the relationship between income in 1970 and standardised mortality rate ratio during the years 1970–1980 for men who were between 20 and 69 years old in 1970 and belonged to the labour force in that year. The data are taken from a study made by Statistics Norway (Statistisk sentralbyrå, 1971; Borgan and Kristofersen, 1986). There is only a very weak relationship between income and mortality in this data set. A second order polynomial fits the data best, but explains merely 9% of the variance in mortality. For the range of observations represented in Fig. 4, the polynomial does, however, show that mortality rate declines monotonically as income increases.

Fig. 5 shows the relationship between income per capita and standardised mortality rate ratio for 25 districts in the town of Oslo, the capital of Norway (Oslo kommune, 1997). The standardised mortality rate ratio was estimated in the same way as for counties (see the comments to Fig. 3 above). Mortality was adjusted for age, but not for sex. Fig. 5 shows that mortality declines as income increases. A geometric function best fits the data and explains about 52% of the variance in standardised mortality rate ratio.

Based on the functions fitted to the data sets presented in Figs. 1–5, the income loss that induces an additional statistical death has been estimated. Estimates were based on the slope of the function best fitting each data set evaluated at the highest level of income. To illustrate, consider the time series data presented in Fig. 2. According to the function fitted to these data, estimated mortality (adjusted for age and sex) during 1991–1995 was 796.675 per 100 000 inhabitants. There were 46 597 deaths in Norway in 1993 (the mid-year of the 1991–1995 period). One additional death represents an increase of 0.00214% in death rate, or an increase of estimated mortality to 796.692. According to the function, this implies a mean income per capita of 186 430 Norwegian kroner (NOK) in 1993. Actual mean income in 1993 was 186 440 NOK. Hence an income loss of 10 NOK per capita, corresponding to 43 248 150 NOK (1993-prices) for the whole population of Norway, would generate one additional statistical death. The other estimates were derived in the same manner. Table 1 presents the estimates. In addition to the estimates based on Figs. 1–5, Table 1 presents an estimate for Norway given in Table A1 in the Appendix A to the paper by Lutter and Morrall (1994). The slope of the function fitted to the county data (Fig. 3) changed sign. The value of the loss of income that induces an additional statistical death was therefore indeterminate for this data set.

The estimated loss in income that induces an additional statistical death ranges from a little more than 25 million NOK to nearly 317 million NOK (3.8–47.5 million US dollars). These estimates are in the same

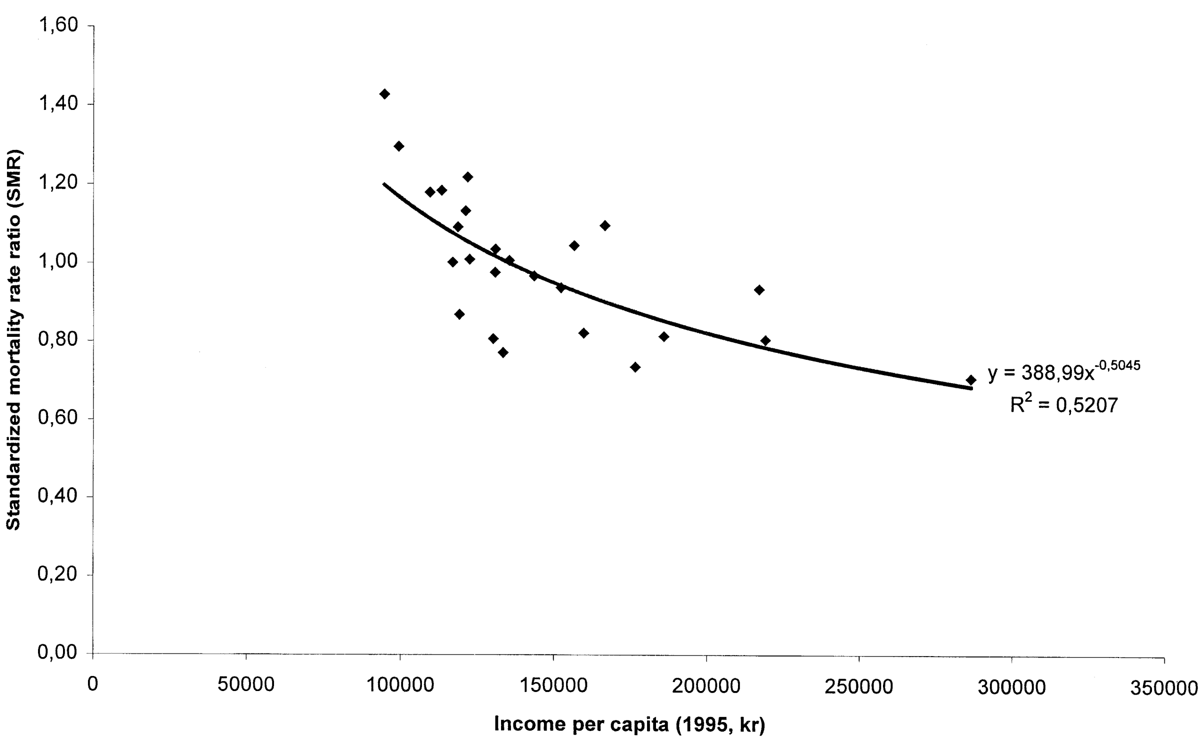

Fig. 5. Relationship between mean income per person in 1995 and standardised morality rate ratio (standardised by age) for 25 districts of Oslo, Norway.

Table 1
Summary of estimates of the loss in real income per capita leading to one additional death in Norway[a]

Source of estimate	No. of data points	Squared correlation coefficient	Death rates adjusted for	Income loss inducing one statistical death (NOK 1995-prices)
Combined cross section and time series data for 101 countries, analysed by Lutter and Morrall (1994) (Table A1)	202	0.83	Health care spending	46 150 000
Cross section data for 101 countries given Lutter and Morrall (1994) (Appendix A, Fig. 1)	101	0.59	Crude rate	316 610 000
Time series data for Norway 1946–1995, given by Statistics Norway, 1996 and 1997 (Fig. 2)	10	0.87	Age, sex	44 930 000
Cross section data for 19 countries in Norway 1992, given by Statistics Norway, 1994 and The Municipality of Oslo, 1997 (Fig. 3)	19	0.22	Age	Indeterminate
Cross section data for 13 occupations in Norway 1970, given by Borgan and Kristofersen (1986) (Fig. 4)	13	0.09	Restricted to men (20–69)	25 380 000
Cross section data for 25 districts in Oslo 1995, given by The Municipality of Oslo, 1997 (Fig. 5)	25	0.52	Age	84 920 000

[a] 1 Norwegian kroner (NOK) = 0.1582 US dollar at 1995 exchange rate.

order of magnitude as those found in most other studies (see, for example, Lutter and Morrall, 1994). In the subsequent analysis of the potential effects on general mortality of trying to implement Vision Zero for traffic accident fatalities, the range of these values is used. This indicates the span of the possible outcomes for overall mortality of trying to implement Vision Zero.

5. A hypothetical programme designed to implement Vision Zero

Vision Zero is still only a long-term vision for road safety. The most cost-effective way of realising the vision is unknown. In fact, one of the ideas underlying Vision Zero is to stimulate the development of new safety measures. It stands to reason that both the costs and safety effects of new, as yet not invented safety measures, cannot be known. The estimates presented in this paper are therefore illustrative only. The results should be taken as highly preliminary, forming a basis for further discussion rather than definite conclusions. Nevertheless, the estimates do indicate, at least within an order of magnitude, the limit to the costs that can be incurred in order to realise Vision Zero before it becomes counterproductive in terms of total mortality.

A purely hypothetical programme consisting of 20 safety measures has been developed in order to estimate the costs and benefits of trying to realise Vision Zero. The programme was based on a review of studies that have evaluated the cost and effects of road safety measures (Elvik et al., 1997). It is intended to include the most cost-effective measures. Details of the programme are given in the Appendix A. It consists of safety measures in five main areas.

1. Regulation of permitted forms of motor travel and permitted speed:

It has been assumed that the use of mopeds and motorcycles is banned. These vehicles are chiefly used for recreational travel and can, to the extent they are used for commercial transport, easily be replaced by cars that provide far better injury protection. Moreover, it has been assumed that roads are reclassified and new speed limits introduced according to the following principles (Wramborg, 1998): (a) Motor vehicles are allowed to drive at walking speed (about 7 km/h) on residential streets where children are allowed to play outdoors. (b) Motor vehicles are allowed to drive at a maximum speed of 30 km/h on streets with mixed traffic, that is, streets in which pedestrians and cyclist use the same traffic lanes as motor vehicles and are allowed to cross the road anywhere. (c) Motor vehicles are allowed to drive at a maximum speed of 50 km/h on urban main streets, provided all pedestrian crossings are grade separated and bicycles have their own road system, which is clearly separated from motor traffic. When pedestrian crossings are at grade, speed is reduced to 30 km/h. (d) Motor vehicles are allowed to drive at a maximum speed of 70 km/h on rural roads, provided no pedestrians and cyclists are allowed on these roads, and provided there is protection against head on collisions in the form of a guard rail between opposing traffic directions. If there is median, in addition to guard rails, a speed of 90 km/h is allowed.

2. Application of intelligent transport system technology:

It has been assumed that all cars have to be equipped with a computer and accessory equipment that performs the following functions: (a) A crash recorder, recording, for example, speed, braking and steering wheel movements during the last seconds preceding a crash. (b) An ignition interlock device, making it impossible to start the car without fastening the seat belt and passing a breathalyser test for alcohol. (c) A speed governor, communicating with speed limit signs and making it impossible to drive faster than the posted speed limit. It has been assumed that all speed limit signs are equipped with transmitters that can communicate with the car computer. (d) An intelligent cruise control device that gives drivers a warning, and possibly also activates the brakes, when the headway to vehicles in front becomes too short. Computers designed to perform these functions will have to be retrofitted into all cars.

3. Modification of vehicles:

Vehicles will be modified to provide improved crash protection by means of the following modifications: (a) High mounted stop lamps will be required on all new cars and retrofitted on all old cars. (b) Some form of front padding, designed as a crash cushion, will be required on all trucks and buses in order to absorb energy in frontal impacts with light vehicles. (c) Seat belts will be required for all seats in buses.

4. Modification of road system:

All roads will first be reclassified according to the speed limit system described above. Once reclassified, roads will be modified so that cross section and alignment is consistent with the design speed and the in-

Table 2
Contributions of 20 safety programmes to the realization of Vision Zero for traffic accident fatalities in Norway[a]

Measure	Target group of accidents or injuries	Current no. of fatalities	Marginal no. of fatalities prevented	Marginal cost of implementation (million NOK)
Pedestrian reflectors	Pedestrian in darkness	15	4.6	175
Crash recorder	All accidents	300	38.0	
General reinforcement	All accidents	300	9.5	131
Median rail guard	Head on collisions	10	1.6	31
Seat belt enforcement	Car passengers	14	1.6	42
Banning motorcycles	Motor cycle accidents	28	16.8	467
Improve road lighting	Accidents in darkness	30	7.6	247
Pedestrian tunnels	Pedestrian crossings	2	0.8	27
Ignition interlocks	Drunk drivers	42	25.3	918
Speed limit system	All accidents	300	57.6	3739
Front padding for trucks	Head on collisions	45	2.9	258
Woonerfs	Accidents in access roads	9	4.9	628
New road lighting	Accidents in darkness	40	15.2	2619
Cycle helmet law	Cyclist accidents	10	0.8	152
High mounted stop lamps	Rear end collisions	7	0.2	40
Upgrade pedestrian crossings	Pedestrian crossing	3	1.0	259
Clear recovery zones	Run off road accidents	87	0.6	219
Intelligent cruise control	Rear end collisions	7	2.2	1491
Seat belts in buses	Bus passengers	3	0.4	290
Three lane median	Head on collisions	90	20.0	22192

[a] 1 Norwegian kroner (NOK) = 0.1582 US dollar at 1995 exchange rate.

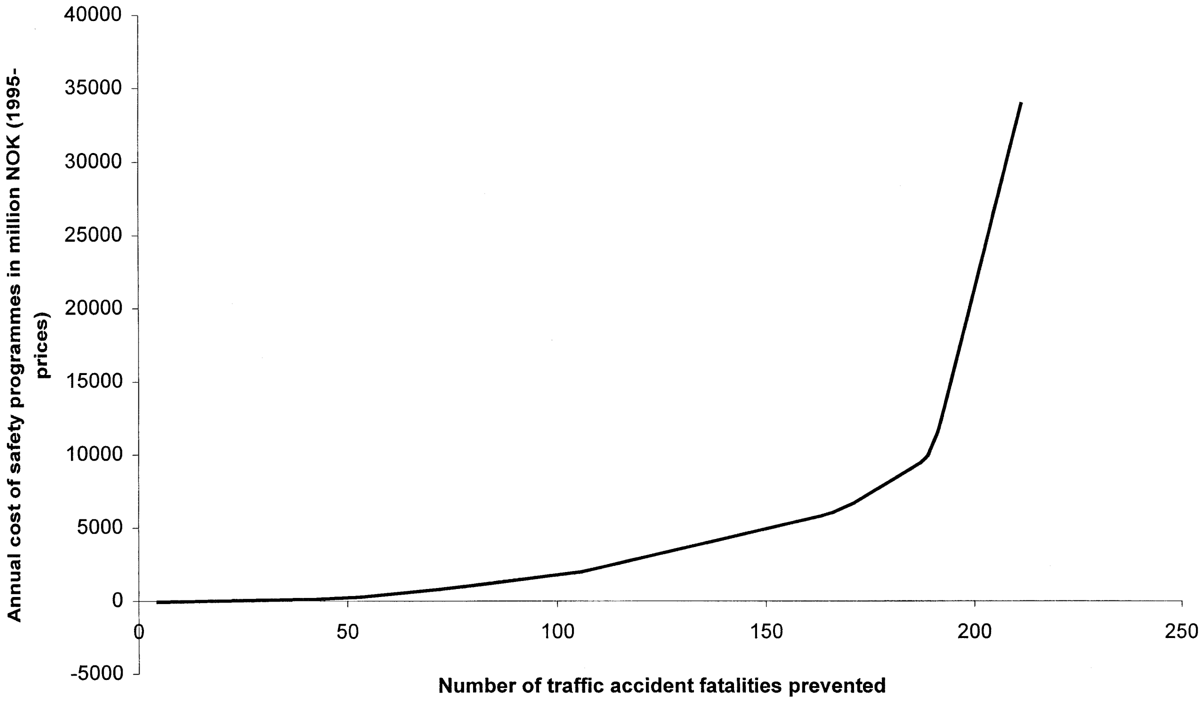

Fig. 6. Marginal cost (in terms of changes in real income per capita) of 20 programmes designed to prevent traffic accidents fatalities in Norway.

tended transport function of the road. This will include the following modifications: (a) All residential streets in urban areas will be modified according to the Woonerf principle. This is a design principle allowing pedestrians, cyclists and motor vehicles to mix at a very low speed (below 20 km/h). (b) Pedestrian crossings on roads where mixed traffic is allowed will be upgraded in order to prevent pedestrians from crossing the road elsewhere and in order to reduce vehicle speed at crossing locations. (c) Grade separated pedestrian crossings (bridges or tunnels) will be constructed on all roads where mixed traffic is not allowed. (d) Existing road lighting will be upgraded. (e) Road lighting will be provided on all public roads. (f) Clear recovery zones will be constructed on roads passing through hazardous terrain. (g) Median guard rails will be provided on all roads that are wide enough to allow at least three traffic lanes (two in one direction, one in the other, alternating every few km). (h) Roads that are currently too narrow for three traffic lanes will be widened and redesigned in order to provide for the system of two plus one lane with a median guardrail.

5. New safety regulations for road users and increased enforcement:

A set of new safety regulations for road users will be introduced, including the following: (a) Mandatory use of retroreflective devices for pedestrians walking in the dark. (b) Mandatory wearing of bicycle helmets. (c) Police enforcement, targeted particularly at passenger use of seat belts in cars and buses, will be increased substantially.

The Appendix A describes in detail how the effects on road safety of the programme have been estimated. Before presenting the results of these calculations, a few remarks are needed concerning how the effects on income of the programme have been estimated. Income can be defined as the value of the results of production (goods and services), measured in monetary terms (Einarsen et al., 1975; Usher, 1987). This value is usually measured by reference to the market demand for goods and services (including labour that is needed as an input to production). However, the products that constitute the safety programme described above, are, with a few exceptions, not sold on a market. Implementing the programme does, on the other hand, require as inputs goods and services that have a market value (for example, computers installed in cars, guard rails on public roads, etc.).

The safety measures included in the programme are all investments. In general, the effect of an investment on income is defined as the returns on the invested capital. In short: an investment increases income if it generates a stream of payments to the investor whose present value exceeds the amount invested. Otherwise, investment decreases income. The effects on income of the road safety investments included in the hypothetical Vision Zero programme have been defined as follows. The returns on the amounts invested, in terms of income gains, consist of:

1. Reduction in vehicle operating costs for commercial vehicles;

2. Reduction in the costs of travel time for commercial vehicles;
3. Reduction in the direct and indirect costs of road accidents. These costs consist of: (a) Medical expenses; (b) repair or replacement of damaged vehicles and other property; (c) administrative costs related to accidents (mainly insurance administration); (d) loss of output due to deaths, permanent incapacitation or temporary absence from work due to injuries.

These items are, at least in principle, included in the gross national product and are, accordingly, comparable to the definition of income used when estimating the relationship between income and mortality. The definition of savings in accident costs is generous. Some economists (Koopmanschap and Ineveld, 1992; Koopmanschap et al., 1995) argue that accidents result only in short term losses of output during the time it takes to replace an accident victim by a new employee (the friction cost method of estimating accident costs). All investment costs have been converted to annuities. The effect on income of the hypothetical safety programme is defined as:

$$\text{Net effect on income} = \text{Amount invested (annuity)} - \text{Returns on investment}$$

It follows that some of the investments will increase income, if the returns as defined above exceed the amount invested (expressed as an annuity). Measures that increase income will have a negative net cost of implementation.

6. Effects of the hypothetical Vision Zero programme on income, traffic fatalities and general mortality

The Appendix A describes in details how the costs, effects on income and safety effects of the hypothetical Vision Zero programme were estimated. Table 2 gives the main results.

In Table 2, the measures that constitute the programme have been listed in order of decreasing cost-effectiveness. The cost-effectiveness of a measure was defined in terms of the number of traffic fatalities prevented per million NOK (net cost) spent to implement the measure. When estimating the marginal contribution of each measure to the prevention of traffic accident fatalities, account was taken of the interaction between several measures affecting the same accidents. If, for example, one measure reduces the number of fatalities by 50% and the other by 60%, their combined effect cannot be 110%. Rather, it is estimated as $(1-0.5)\times(1-0.6)=0.8=80\%$ reduction.

The current number of road accident fatalities in Norway is about 300 per year. According to Table 2, it is possible to reduce this number by 212, to 88 per year, by implementing the hypothetical Vision Zero pro-

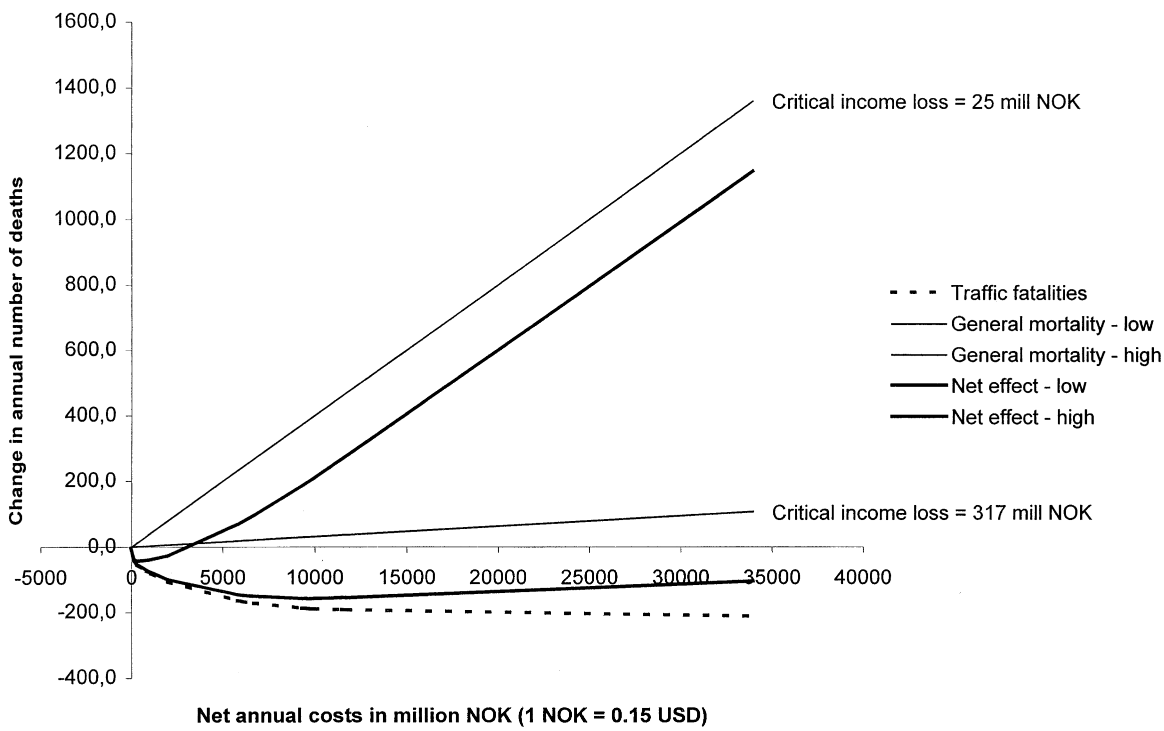

Fig. 7. Effects of 20 programmes designed to prevent traffic accident fatalities in Norway on traffic accident mortality an on general mortality. Change in number of deaths per year.

Table A1
Traffic volume and number of police reported accidents on public roads in Norway

Type of road and speed limit	Million vehicle kilometres per year (1994)				Accidents	
	Total	Cars	Trucks	Buses	Injury	Fatal
Motorway class A	830	745	83	2	58	2
Motorway class B	1030	930	90	10	103	12
Main road 90	635	577	55	3	75	8
Main road 80	11100	10207	710	183	1887	104
Main road 70	1120	1040	70	10	225	11
Main road 60	3800	3565	195	40	1025	32
Suburban main 50	1820	1715	85	20	850	18
Urban main 50	1135	1076	47	12	674	13
Total main roads	21480	19865	1335	280	4913	200
Rural collector	2600	2482	100	18	660	23
Suburban collector	1235	1181	45	9	560	12
Urban collector	165	157	5	3	97	2
Total collectors	4000	3820	150	30	1317	37
Rural access	660	610	40	10	265	8
Suburban access	1160	1125	25	10	870	9
Urban access	860	820	20	20	873	8
Total access	2680	2555	85	40	2008	25
Private roads	526	526	0	0	317	8
All roads	28686	26766	1570	350	8555	270

gramme. Although the target of zero fatalities is not attained, a substantial reduction in the number of fatalities is clearly possible.

Fig. 6 shows the marginal cost function for the hypothetical Vision Zero programme. The costs rise slowly for the first 180–190 fatalities prevented. Then the costs rise very rapidly. The sharp rise in marginal costs is entirely due to the costs of redesigning and widening rural roads in Norway to allow three traffic lanes with a median. The costs of this measure are prohibitively high in view of the rather modest impact on fatalities (about 20 prevented fatalities).

The effects of the hypothetical Vision Zero programme on general mortality were estimated by assuming that an income loss of either 25 million NOK (low critical value) or 317 million NOK (high critical value) induces an additional statistical death. The results of the estimation are presented in Fig. 7. The dotted line shows the effects on traffic fatalities. The thin straight lines show the effects on general mortality, while the thick lines in the middle shows the net effects on mortality, taking into account both the effects on traffic fatalities and general mortality. To derive Fig. 7, measures were arranged in order of decreasing cost-effectiveness.

Fig. 7 shows that the estimate used for the income loss that leads to an additional death has a crucial influence on the results. Assuming that a loss of income of 25 million NOK is sufficient to induce an additional death, the net effect of the hypothetical Vision Zero programme is an increase in overall mortality of 1143 (212 fewer traffic deaths, 1355 additional deaths from increase in general mortality). If, on the other hand, a critical income loss of 317 million NOK is assumed, there will be no overall increase in mortality. (212 fewer traffic deaths, 107 additional deaths from increase in general mortality, for a net gain of 105). Even in this case, however, the increase in general mortality starts eating up the reduction in traffic deaths when the 17 most cost-effective measures of the programme have been implemented. These results show that, in principle, one cannot rule out the possibility that society may spend so much trying to eliminate traffic accident fatalities, that the consequent loss in income leads to an increase in general mortality that more than offsets the decline in traffic accident fatalities.

7. Discussion

To many people, the very idea of putting limits to life saving efforts based on economic criteria is morally reprehensible. Human life, it is argued, is infinitely valuable. It cannot, and should not, be reduced to a tradable commodity akin to apples and oranges. Safety, it is argued, is not something we purchase like a newspaper. It is a basic human right to be protected from fatal accidents. Humans are fallible; they make mistakes in traffic, but these mistakes should not carry the death penalty. It is therefore the moral obligation of those who design cars, roads and the rules of the road to do their utmost to protect road users from being killed in traffic. Proponents of Vision Zero for traffic fatalities ask rhetorically if someone could please tell them the optimal number of traffic accident fatalities.

Superficially, these arguments are very attractive. To argue against an ideal of zero fatalities in traffic looks like a hopeless cause. By claiming the moral high ground, proponents of Vision Zero make critics look like heartless cynics who not merely tolerate the deaths of innocent people as an unavoidable tragedy, but actually argue that these deaths are, in some sense, desirable.

This paper has argued that proponents of Vision Zero for traffic fatalities overlook a few basic facts of life. The first ethical rule underlying Vision Zero can be interpreted as approval of an objective of maximising life saving in general. Such an objective, however, has the rather startling implication that a survival lottery has to be introduced, at least as long as there is a shortage of organs for transplantation. Advocates of Vision Zero are, like most other people, likely to recoil at this implication. Surely, it can never be right to kill, even if by doing so more people will survive than would otherwise be the case. An objective of eliminating a specific cause of death could imply that there is so much less resources available to control other causes of death that overall mortality increases. Most of this paper has been devoted to investigating if Vision Zero does indeed have such an implication.

The analysis relies on a number of assumptions that can be questioned. First, is there really a causal relationship between income per capita and mortality rates? Second, if there is, is it obvious that the causal direction goes from income to mortality and not the other way around? Third, how reasonable and reliable are the estimates of the income loss that induces an additional statistical death? Fourth, how reasonable and reliable are the estimates of the costs and effects of the hypothetical safety programme designed to implement Vision Zero? Each of these issues will be discussed in turn.

A detailed discussion of criteria for assessing causality in a statistical relationship is impossible in this paper. Frequently used criteria of causality include: (a) There must be a statistically significant relationship between cause and effect. (b) The direction of causality must be clear. (c) The relationship between cause and effect should be reproduced consistently in several studies. (d) The relationship between cause and effect should persist when important confounding variables are controlled. (e) There should be a dose-response pattern between cause and effect. (f) There should be a plausible biological (including behavioural) mechanism that explains the relationship between cause and effect (see, for example, Elwood, 1988 for further discussion).

Table A2
Current mean speed, Vision Zero speed, current number of accidents and Vision Zero accidents on public roads in Norway[a]

Type of road and speed limit	Mean speed km/h		Current accidents		Vision Zero accidents	
	Current speed	Vision Zero speed	Injury	Fatal	Injury	Fatal
Motorway class A	95	88	58	2	50	1
Motorway class B	87	68	103	12	63	4
Main road 90	85	68	75	8	48	3
Main road 80	75	68	1887	104	1551	70
Main road 70	70	68	225	11	212	10
Main road 60	59	48	1025	32	678	14
Suburban main 50	50	48	850	18	783	15
Urban main 50	35	28	674	13	431	5
Total main roads	66	57	4913	200	3806	123
Rural collector	65	65	660	23	660	23
Suburban collector	40	40	560	12	560	12
Urban collector	30	28	97	2	84	2
Total collectors	52	52	1317	37	1304	37
Rural access	60	60	265	8	265	8
Suburban access	35	35	870	9	870	9
Urban access	25	15	873	8	314	1
Total access	34	26	2008	25	1449	18
All roads	60	52	8555	270	6897	186

[a] The effects of the Vision Zero speed limit system on the number of accidents were estimated according to the following functions:

Injury accidents after/injury accidents before = (mean speed after/mean speed before)^2.

Fatal accidents after/fatal accidents before = (mean speed after/mean speed before)^4.

Table A3
Zero order effects, residual factors and marginal effects of the twenty measures

	Zero order effects		Residuals		Marginal effects	
Measure	Fatalities	Injuries	Fatalities	Injuries	Fatalities	Injuries
Banning motorcycles	26.6	1100	0.911	0.908	16.8	801
Speed limit system	91.0	2370	0.697	0.802	57.6	1726
Ignition interlock	39.9	505	0.867	0.958	25.3	368
Crash recorder	60.0	1748	0.800	0.854	38.0	1273
Intelligent cruise control	3.5	850	0.988	0.929	2.2	619
High mounted stop lamps	0.3	100	0.999	0.992	0.2	73
Seat belts in buses	0.6	16	0.998	0.999	0.4	12
Cycle helmet law	1.3	85	0.996	0.993	0.8	62
Pedestrian reflectors	7.2	140	0.976	0.988	4.6	102
Front padding of trucks	4.5	40	0.985	0.997	2.9	29
Woonerfs	7.8	775	0.974	0.935	4.9	564
Upgrade pedestrian crossings	1.5	50	0.995	0.996	1.0	36
Grade separated crossings	1.2	40	0.996	0.997	0.8	29
Upgrade road lighting	12.0	200	0.960	0.983	7.6	146
New road lighting	24.0	250	0.920	0.979	15.2	182
Median guard rails	2.5	10	0.992	0.999	1.6	7
Widening roads and median	31.5	450	0.895	0.962	20.0	328
Clear recovery zones	1.0	27	0.997	0.998	0.6	20
Seat belt enforcement	2.5	38	0.992	0.997	1.6	28
General enforcement	15.0	290	0.950	0.976	9.5	211

Four of the six estimates in Table 1 of the loss of income that induces an additional statistical death are statistically significant at the five percent level. For the county data, the sign of the relationship was equivocal, while the estimate based on occupational groups was not significant. Viscusi (1994a) reports a large number of estimates of the income loss that induces a statistical death; presumably all of them are statistically significant. The estimates range from 1 to 138 million US Dollars (1990). Viscusi (1994b) presents seven estimates from previous studies without commenting on their statistical significance (range 1.9–33.2 million US Dollars 1992) and presents a new estimate based on the Superfund programme for hazardous waste sites (35.7 million US Dollars 1992). Lutter and Morrall (1994) quote 13 previous estimates (their list overlaps the one given by Viscusi, 1994b) in addition to giving several new estimates based on their own data (range 6.3–19.4 million US Dollars for estimates based on US data). Smith et al. (1994) reanalysed the data set for 101 countries used by Lutter and Morrall (1994), adding the number of women of childbearing age as a percentage of all women and a measure of each country's literacy rate as potentially confounding variables. The addition of these variables to the data substantially weakened the relationship between income and mortality. A non-significant estimate of an income loss of 96 million dollars leading to one statistical death was derived. Chapman and Hariharan (1994) present an estimate that controls for initial health state, but still find that a decline in income of 12.2 million US dollars induces an additional death. Finally Keeney (1997) estimates the income loss that induces an additional death to between 4.9 and 13.3 million US dollars.

Nearly all the estimates of the loss in income that generates an additional death for which information is given about statistical significance are statistically significant at conventional levels. All estimates are consistent as far as the sign of the relationship is concerned, in that all indicate that a loss in income increases mortality. The estimates do, however, vary substantially as far as the size of the loss in income that induces an additional death is concerned. The range in the studies quoted above goes from 1 million US dollars to 138 million US dollars (values for different years). To a large extent, this great diversity is probably attributable to the choice of method for estimating the effects of changes in income on mortality. Broadly speaking, two methods have been used. Most studies estimate the direct relationship between income and mortality, while controlling for various confounding variables. Viscusi (1994a,b, 1996), on the other hand, rejects this approach for two reasons.

In the first place, Viscusi argues that it is difficult to estimate the causal effect of income on mortality in a sufficiently well controlled manner, because mortality is affected by so many other variables for which data are not always available. In the second place, Viscusi finds the results of studies of the direct relationship between income and mortality hard to reconcile with the results of studies of the willingness-to-pay for a risk reduction corresponding to the prevention of one fatality, often referred to as the value of a statistical life. Putting the best estimate for the value of a statistical life at 5 million US dollars, Viscusi (1996) points out that studies of the direct relationship between income and mortality seem to imply that with an expenditure of about double that amount, there will be the loss of a statistical life. His alternative method of estimating the expenditure that leads to the loss of a statistical life, which is based on the marginal propensity to spend on health care, leads to an estimate of about 50 million US dollars.

It is beyond the scope of this paper to evaluate Viscusi's arguments in detail. Only two points will be noted. First, it cannot be ruled out that the willingness-to-pay for reduced risk has been overestimated in some studies. The value of a statistical life may therefore be smaller than the 5 million dollars Viscusi regards as the best estimate. Second, Viscusi (1996) notes that if the entire gross national product of the US were devoted to avoiding fatal accidents, it would amount to only 55 million dollars per accident fatality (assuming these fatalities could be eliminated). However, Viscusi has estimated that an expenditure of about 50 million dollars leads to the loss of a statistical life. This apparently implies that one could spend almost the entire gross national product of the US on safety before the decline in income lead to increased mortality. This seems unreasonable.

No study has controlled for every important confounding variable when estimating the effect of income on mortality. One of the estimates in Table 1 controlled for age and sex, two others for age, one controlled for health care spending, one was restricted to men between the ages of 20 and 69 and one used crude mortality rate. With one exception, all estimates indicated that higher income is associated with reduced mortality.

An obvious objection to treating income as a cause of mortality is that the causal direction could be the other way around. Poor health (due, for example, to congenital defects) may lead both to low income and high mortality. However, a study by Chapman and Hariharan (1994), controlling for initial health state, still found an effect of income on mortality. The causal influence probably goes in both directions.

It is not difficult to imagine a number of pathways through which a high income could lead to better health and, in turn, low mortality. Rich people can afford better food and houses than poor people can. They often live in less polluted neighbourhoods with less crime. Rich people can afford better health care and often belong to social networks that help them in getting access to scarce medical treatments. Education correlates with higher income and improves health knowledge and practices. Studies of the relationship between income and mortality at an aggregated level do not, however, uncover these pathways. The credibility of these studies would increase if the relationship of income to health related behaviour at the individual level could be demonstrated.

A study of factors affecting mortality in 25 municipal districts in the city of Oslo (Rognerud and Stensvold 1998) goes some way towards uncovering the pathways through which income is related to mortality. The study shows, for example, that the proportion of daily smokers is highest in the most deprived districts of Oslo. Although these data are at an aggregated level, they strongly suggest that smoking is more common in low income groups than in high income groups. Moreover, the percentage of smokers in their population is strongly related to the percentage who are physically inactive. Both smoking and lack of exercise are known to increase mortality.

The realism of the hypothetical Vision Zero programme is difficult to assess. Most of the estimates of both costs and safety effects of the twenty measures that constitute the programme are based on previous evaluation studies. In a few cases, purely hypothetical estimates have been made. This is true of, for example, front padding of trucks. In general, the estimates are optimistic in that: (1) a high level of compliance with new regulations has been assumed; (2) no behavioural adaptation among road users has been assumed to take place. It is therefore probably fair to say that the estimated costs and safety effects of the hypothetical Vision Zero programme are somewhat biased in favour of Vision Zero. It was felt that this was a conservative approach, in view of the potentially serious implications for Vision Zero of the main argument made in this paper—that Vision Zero may in fact kill more people than it saves.

An objection to the analysis is that more emphasis should be put on preventing road accidents than other causes of death, because road accidents disproportionately shorten life expectancy (Sunstein, 1997). The mean loss of life expectancy for someone killed in a road accident in Norway is about 38 years. The mean loss of life expectancy from any cause of death is about 14 years. Hence, a programme that reduces traffic deaths may increase overall life expectancy even if the programme causes an increase in general mortality. This will at least be the case if the additional deaths from other causes are not more than about 2.5 times as numerous as the prevented traffic deaths. As shown in this paper, however, it cannot be ruled out that, in the worst case, the increase in general mortality resulting from the hypothetical Vision Zero programme will be so large that it more than offsets the reduction in traffic deaths, even in terms of life expectancy.

8. Conclusions

This paper has presented a preliminary analysis of some possible implications of trying to implement Vision Zero for traffic accident fatalities. Vision Zero is a long-term target for road safety proposed by the Swedish National Road Administration, stating that nobody should be killed or seriously injured in traffic.

Vision Zero is a visionary target. It is impossible to know its full implications at the present time. The analyses presented in this paper should therefore be regarded as preliminary and illustrative only. The main points can be summarised as follows:

1. An objective of minimising overall mortality implies that a survival lottery must be introduced, at any rate as long as there is a shortage of organs for transplants. A survival lottery is a scheme in which people are drawn at random to sacrifice their life for the benefit of others.
2. An objective of eliminating a certain cause of death, like traffic accidents, may be so expensive to realise that it reduces resources available to control other causes of death and thus increases general mortality.
3. The amount of resources available to control general mortality in a society can be measured in terms of income per capita. Several analyses of the relationship between income per capita and general mortality based on Norwegian data show that there is a negative relationship between income and mortality.
4. The loss of income that induces an additional statistical death is estimated at between 25 and 317 million NOK (3.8–47.5 million US dollars) based on Norwegian data. These estimates are in line with those of most previous studies.
5. No study of the relationship between income and mortality fully satisfies commonly used criteria of causality. However, the balance of evidence suggests that the relationship between income and mortality is a causal one.
6. A hypothetical programme designed to implement Vision Zero for traffic fatalities was developed and its effects on the number of fatalities estimated. Implementing the whole programme could reduce the number of traffic deaths in Norway from about 300 per year to about 90 per year.
7. Applying the lowest estimate of the income loss that induces an additional death (25 million NOK), it was estimated that implementing the entire hypothetical Vision Zero programme would increase general mortality by about 1355. This would lead to a net increase of about 1145 deaths per year (1355 minus 210 prevented traffic deaths).
8. Applying the highest estimate of the income loss that induces an additional statistical death (317 million NOK), it was estimated that implementing the entire hypothetical Vision Zero programme would increase general mortality by about 110. In this case, there would not be an increase in overall mortality.
9. The analyses presented in this paper show that the possibility cannot be ruled out that a massive effort to eliminate traffic deaths would be counterproductive in terms of overall mortality. This possibility must be regarded as a moral dilemma by advocates of Vision Zero, who have invoked the ethical principle that 'One must always do everything in one's power to prevent death or serious injury' to justify the vision.

Appendix A. A hypothetical Vision Zero programme

A.1. Description of current road system and accidents

Table A1 contains a description of public roads in Norway. The table shows traffic volume in million vehicle kilometres of travel and the number of accidents recorded by the police. Only injury accidents are recorded. The number of injury accidents listed in Table A1 includes fatal accidents. The numbers given are annual mean numbers for the years 1991–1994. In general, roads in rural areas have a speed limit of 80 km/h. On motorways (freeways) and a few other roads, this limit has been raised to 90 km/h. Roads in urban areas have a speed limit of 50 km/h. In suburban areas, the speed limit is generally 60 or 70 km/h.

A.2. The effects of basic speed regulations in Vision Zero

According to Vision Zero, the following general speed regulations apply: On streets where children play a maximum driving speed of 7 km/h is allowed. On streets with mixed traffic (pedestrians and cyclists mixed with motor vehicles) a maximum driving speed of 30 km/h is allowed. On urban main streets, a maximum driving speed of 50 km/h is allowed. On rural roads, except motorways of class A, a maximum driving speed of 70 km/h is allowed. Table A2 shows current driving speed on Norwegian roads and the speed that is assumed to obtain if Vision Zero is implemented. The Table also shows the estimated number of accidents when the Vision Zero speed limit system has been implemented.

A.3. Unit costs of accidents and travel time

The net effects income of the hypothetical Vision Zero programme are defined as the difference between income spent to implement the measures and income gained as a result of the benefits, in terms of items recorded in the gross national income, of those measures. To measure benefits, the following cost rates have been applied for accidents and travel time:

Cost of a fatal accident	3 940 000 NOK
Cost of a non-fatal injury accident	670 000 NOK
Cost of one vehicle hour in traffic for trucks	272 NOK
Cost of one vehicle hour in traffic for buses	244 NOK

A.4. Estimated effects of individual measures in Vision Zero programme

The hypothetical Vision Zero programme consists of 20 safety measures. On the following pages, the effects of these measures are estimated. The estimates presented in this section concern the zero order effects of the measures. The zero order effects are the effects each measure has if implemented on its own and provided everything else remains unchanged. Investment costs have been converted to an annuity. A depreciation period of 7 years has been assumed for vehicle related measures, 5 years for helmets and reflective devices, 25 years for road investments and 1 year for police enforcement.

Measure	Banning the use of mopeds and motorcycles.
Target injuries	Injuries in accidents in which mopeds or motorcycles are involved.
Current number	28 fatalities and 1168 injuries per year (official statistics).
Effect on injuries	95% compliance is assumed, implying that 95% of fatalities and injuries are prevented.
Zero order effect	26.6 fatalities and 1100 injuries prevented per year.
Implementation costs	No direct implementation costs have been assumed.
Income lost	Motorcycle dealers lose business worth about 900 mill NOK per year (based on Statistisk sentralbyrå, survey of household consumption, 1994).
Income gained	Savings in accident costs of 433 mill NOK per year.
Net effect on income	Net loss of 457 million NOK per year (900–433).

Measure	Requiring speed governor adjoined to new speed limit system in all cars, including transmitters on speed limit signs.
Target injuries	All injuries.
Current number	300 fatalities and 11 950 injuries per year (official statistics).
Effect on injuries	The mean speed of travel is reduced from 59.7 to 51.9 km/h.
Zero order effect	Based on the functions given above the number of fatalities is reduced by 91.0 and the number of injuries reduced by 2370 per year.
Implementation costs	Retrofitting a speed governor (including transmitters on highway signs) is assumed to cost 8000 NOK per car. Total investment is 16 480 million NOK, corresponding to an annuity of 3065 million NOK (7 years). Annual additional costs for new cars is estimated to 520 million NOK (130 000 new cars per year at a cost of 4000 NOK per car). Total implementation costs 3585 million NOK per year.
Income lost	Additional costs for commercial transport amounts to 1,150 mill NOK per year.
Income gained	Savings in accident costs of 996 million NOK per year.
Net effect on income	Net loss of 3739 per year (3585 + 1150–996).

Measure	Ignition interlock device for seat belts and alcohol. Car cannot be started without fastening seat belts and passing a breathalyser test.
Target injuries	Injuries involving unbelted or alcohol impaired drivers.
Current number	Based on Elvik (1997) the current number is estimated to 42 fatalities and 535 injuries per year.
Effect on injuries	95% compliance is assumed, implying that 95% of target injuries are eliminated.
Zero order effect	39.9 fatalities and 505 injuries prevented per year.
Implementation costs	Based on Glad (1996) a cost of installing an ignition interlock system of 1000 NOK per car has been as-

	sumed. This amounts to 2060 million NOK in total, or 383 million NOK as an annuity (7 years). In addition, there is an annual cost of 65 million for new cars and an annual inspection cost for the system of 350 NOK per car, or 721 million NOK in total. Total implementation costs 1169 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 251 million NOK per year.
Net effect on income	Net loss of 918 million NOK per year (1169–251).

Measure	Crash recorder in all cars. Records speed, braking, use of indicators and steering wheel movements before crash.
Target injuries	All injuries.
Current number	300 fatalities and 11 950 injuries per year (official statistics).
Effect on injuries	Based on Wouters and Bos (1997) a reduction of 20% in the number of fatalities and 15% in the number of injuries is assumed.
Zero order effect	60.0 fatalities and 1748 injuries prevented per year.
Implementation costs	A cost of 2000 NOK per car is assumed, amounting to an investment of 4120 million NOK for the current car fleet or 766 million NOK as an annuity (7 years). In addition, there will be costs of 130 million NOK for new cars each year. Total implementation costs 896 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 721 million NOK per year.
Net effect on income	Net loss of 175 million NOK per year (896–721).

Measure	Intelligent cruise control giving drivers a warning when the headway to the vehicle in front becomes too small.
Target injuries	Injuries in rear end collisions.
Current number	Seven fatalities and 1890 injuries per year (official statistics).
Effect on injuries	Based on Elvik et al. (1997) the device is assumed to reduce the number of injuries in rear end collisions by 50%.
Zero order effect	3.5 fatalities and 850 injuries prevented per year.
Implementation costs	Based on information given by Elvik et al. (1997) a cost of 4000 NOK per car (retrofitting) has been assumed; in total 8240 million NOK or 1533 million NOK as an annuity (7 years). In addition there will be an annual costs of 260 million NOK for new cars. Total implementation costs 1793 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 302 million NOK per year.
Net effect on income	Net loss of 1491 million NOK per year (1793–302).

Measure	High mounted stop lamps on all cars. 36% of cars already have high mounted stop lamps. The measure is to retrofit them on the remaining 64% of cars and require them on all new cars.
Target injuries	Injuries in rear end collisions.
Current number	Seven fatalities and 1890 injuries per year (official statistics).
Effect on injuries	Based on Elvik et al. (1997) high mounted stop lamps are assumed to reduce the number of injuries in rear end collisions by 14%.
Zero order effect	0.3 fatalities and 100 injuries prevented per year (based on Elvik et al., 1997).
Implementation costs	250 NOK per car, 264 million NOK in total, which corresponds to 50 million NOK as an annuity (7 years). In addition there will be an annual operating cost of 26 million NOK. Total implementation costs 76 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 35 million NOK per year.
Net effect on income	Net loss of 41 million NOK per year (76–35).

Measure	Requiring seat belts on all seats in buses. Retrofitting in old buses and standard for new buses.
Target injuries	Injuries to bus occupants.
Current number	Three fatalities and 160 injuries per year (based on Vaa, 1993).
Effect on injuries	Based on Elvik et al. (1997) a highly uncertain effect of 20% reduction in the number of fatalities and 10% reduction in the number of injuries has been assumed.
Zero order effect	0.6 fatalities and 16 injuries prevented per year.
Implementation costs	Based on Elvik et al. (1997) an investment cost of 40 000 NOK per bus has been assumed. Total cost is 1200 or 223 million NOK as an annuity (7 years). In addition there will be a cost of 73 million NOK per year for new buses. Total implementation costs 296 million NOK.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 7 million NOK per year.
Net effect on income	Net loss of 289 million NOK per year (296–7).

Measure	Mandatory wearing of cycle helmets (for pedal cyclists)
Target injuries	Injuries to cyclists (unhelmeted).
Current number	Ten fatalities and 720 injuries per year involving unhelmeted cyclists (official statistics).
Effect on injuries	60% compliance has been assumed. No behavioural adaptation and no change in the amount of cycling have been assumed. Based on Elvik et al. (1997) cycle helmets have been assumed to reduce the probability of a fatal injury when worn by 22%.
Zero order effect	1.3 fatalities and 85 injuries prevented per year.
Implementation costs	It has been assumed (Elvik et al., 1997) that 1 680 000 cyclists will have to buy a helmet at a cost of 400 NOK per helmet. This amounts to a total cost of 672 or 164 million NOK as an annuity (5 years). In addition, an annual enforcement cost of 20 million NOK has been assumed. Total implementation costs 184 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 32 million NOK per year.
Net effect on income	Net loss of 152 million NOK per year (184–32).

Measure	Mandatory wearing of reflective devices for pedestrians in the dark.
Target injuries	Injuries to pedestrians in the dark (not wearing reflective device).
Current number	15 fatalities and 335 injuries per year (official statistics).
Effect on injuries	60% compliance has been assumed. No behavioural adaptation and no change in the amount of walking have been assumed. Based on Elvik et al., (1997) reflective devices have been assumed to reduce the probability of a fatal injury when worn by 80%.
Zero order effect	7.2 fatalities and 140 injuries prevented per year.
Implementation costs	It has been assumed (Elvik et al., 1997) that 18 000 000 reflective devices at a cost of 250 NOK per device are needed. This amounts to a total cost of 45 million NOK or 11 million NOK as an annuity (5 years).
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 62 million NOK per year.
Net effect on income	Net gain of 51 million NOK per year (11–62).

Measure	Front padding of trucks; a crash cushion of about 75 cm mounted on the front of buses and trucks in order to absorb energy in frontal impacts with smaller cars. Retrofitting on all buses and trucks and mandatory for new buses and trucks from a certain date.
Target injuries	Injuries in head on collisions between buses or trucks and smaller cars.
Current number	45 fatalities and 405 injuries per year (official statistics).
Effect on injuries	A highly uncertain effect of 10% reduction in the number of fatalities

	and injuries has been assumed. This is a purely hypothetical estimate.
Zero order effect	4.5 fatalities and 40 injuries prevented per year.
Implementation costs	Based on the costs on underrun guardrails on trucks (Elvik et al., 1997) a cost of 5000 NOK per bus or truck has been assumed (retrofitting). This amounts to a total of 500 or 93 million NOK as an annuity (7 years). In addition, there will be a cost of 188 million NOK per year for new buses and trucks. Total implementation costs 281 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 22 million NOK per year.
Net effect on income	Net loss of 259 million NOK per year (281–22).

Measure	Reconstructing residential streets in towns according to the Woonerf principles. Driving allowed only at walking speed.
Target injuries	Injuries in urban residential streets.
Current number	Nine fatalities and 1210 injuries per year (estimate given in Elvik et al., 1997).
Effect on injuries	Mean driving speed has been assumed to drop from 25 to 15 km/h.
Zero order effect	Based on the functions given above the number of fatalities is reduced by 7.8 and the number of injuries reduced by 775 per year.
Implementation costs	2650 km of street will be reconstructed at a cost of 4 million NOK per km (Elvik et al., 1997). Total costs will be 10 600 or 912 million NOK as an annuity (25 years).
Income lost	No loss of income has been assumed to occur. Effects on travel time accounted for in new speed limit system.
Income gained	Savings in accident costs of 284 million NOK per year.
Net effect on income	Net loss of 628 million NOK per year (912–284).

Measure	Upgrading pedestrian crossings on urban collector streets by means of safety fences, high intensity lighting and raised crossings.
Target injuries	Accidents involving pedestrians crossing the road.
Current number	Three fatalities and 100 injuries per year (estimate based on Elvik et al., 1997).
Effect on injuries	Based on Elvik et al. (1997) a 50% reduction in fatalities and injuries at the upgraded locations has been assumed.
Zero order effect	1.5 fatalities and 50 injuries prevented per year.
Implementation costs	Based on Ward et al. (1994), five crossing locations per km of road has been assumed. This results in a total of 15 000 crossings that need upgrading. The cost of upgrading has been set to 100 000 NOK per crossing (Elvik et al., 1997). Total costs of upgrading will be 1500 or 129 million NOK as an annuity (25 years). In addition, there will be annual operating costs (road lighting) of 10 000 NOK per crossing. Total implementation costs 279 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 20 million NOK per year.
Net effect on income	Net loss of 259 million NOK per year (279–20).

Measure	Construction of grade separated pedestrian crossings (bridges or tunnels) on main streets in urban areas.
Target injuries	Accidents involving pedestrians crossing the road.
Current number	1.5 fatalities and 50 injuries per year (estimate based on Elvik et al., 1997).
Effect on injuries	Based on Elvik et al.,(1997) an 80% reduction in fatalities and injuries at locations where grade separated crossings are constructed has been assumed.
Zero order effect	1.2 fatalities and 40 injuries prevented per year.
Implementation costs	Based on Ward et al. (1994), 1 crossing location per km of road has been assumed. This results in a total of 250 crossings that need reconstruction. The cost of reconstruction has been set to

	2,000,000 NOK per crossing (Elvik et al., 1997). Total costs of upgrading will be 250 or 43 million NOK as an annuity (25 years).
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 16 million NOK per year.
Net effect on income	Net loss of 27 million NOK per year (43–16).

Measure	Upgrading substandard road lighting.
Target injuries	Injuries in the dark on roads with substandard lighting.
Current number	30 fatalities and 1000 injuries per year (estimate based on official statistics).
Effect on injuries	Based on Elvik et al. (1997) it has been assumed that upgrading substandard road lighting reduces fatalities in darkness by 40% and other injuries in darkness by 20% on the roads concerned.
Zero order effect	12.0 fatalities and 200 injuries prevented per year.
Implementation costs	Based on Elvik et al., (1997), it has been assumed that lighting on 11 250 km of road needs upgrading. The cost of upgrading has been estimated to 2637 million NOK, or 226 million NOK as an annuity (25 years). In addition, there will be annual operating costs 113 million NOK in total. Total implementation costs 339 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 92 million NOK per year.
Net effect on income	Net loss of 247 million NOK per year (339–92).

Measure	Installing road lighting on presently unlit roads.
Target injuries	Injuries in the dark on unlit roads
Current number	40 fatalities and 1000 injuries per year (estimate based on official statistics)
Effect on injuries	Based on Elvik et al. (1997) it has been assumed that installing road lighting reduces fatalities in darkness by 60% and other injuries in darkness by 25% on the roads concerned.
Zero order effect	24.0 fatalities and 250 injuries prevented per year.
Implementation costs	Based on Elvik et al. (1997), it has been assumed that lighting must be installed on 70 189 km of road. The cost of this has been estimated to 19 572 million NOK, or 1,698 million NOK as an annuity (25 years). In addition, there will be annual operating costs 1053 million NOK in total. Total implementation costs 2751 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 132 million NOK per year.
Net effect on income	Net loss of 2619 million NOK per year (2751–132).

Measure	Median guardrail on wide roads.
Target injuries	Head on collisions on wide roads.
Current number	Ten fatalities and 200 injuries per year (estimate based on official statistics)
Effect on injuries	Based on Elvik et al. (1997), a 25% decline in the number of fatalities and a 5% decline in the number of injuries has been assumed.
Zero order effect	2.5 fatalities and ten injuries prevented per year.
Implementation costs	Based on Elvik et al. (1997), it has been assumed that median guardrails can be installed on 1000 km of road. The cost of this has been estimated to 400 or 34 million NOK as an annuity (25 years). In addition, there will be annual operating costs 5 million NOK in total. Total implementation costs 39 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 8 million NOK per year.
Net effect on income	Net loss of 31 million NOK per year (39–8).

Measure	Widening narrow roads to three lanes and providing median gurardrails.
Target injuries	Head on collisions on narrow roads.
Current number	90 fatalities and 1800 injuries per year (estimate based on official statistics).

Effect on injuries	Based on Elvik et al. (1997), a 35% decline in the number of fatalities and a 25% decline in the number of injuries has been assumed.
Zero order effect	31.5 fatalities and 450 injuries prevented per year.
Implementation costs	Based on Elvik et al. (1997), it has been assumed that 65 490 km of road needs widening. The cost of this has been estimated to 261 960 million NOK (4 million NOK per km of road), or 22 529 million NOK as an annuity (25 years). Total implementation costs 22 529 million NOK per year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 216 million NOK per year and savings in operating costs of commercial vehicles of 120 million NOK per year (0.1 NOK per vehicle km).
Net effect on income	Net loss of 22 193 million NOK per year (22 529–336).

Measure	Clear recovery zones on roads in hazardous terrain.
Target injuries	Injuries in accidents where vehicle left the roadway.
Current number	87 fatalities and 2690 injuries per year (official statistics).
Effect on injuries	Based on Elvik et al. (1997) a 25% reduction in the number of fatalities and a 10% reduction in the number of injuries have been assumed. It has further been assumed that the measure is carried out on 1% of rural roads with 5 times the normal accident density (accidents per km of road per year).
Zero order	1.0 fatalities and 27 injuries pre-effectvented per year.
Implementation costs	It has been assumed that the measure is carried out on 670 km of road at a cost of 4 million NOK per km. Total cost is 2680 or 230 million NOK as an annuity (25 years).
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 11 million NOK per year.
Net effect on income	Net loss of 219 million NOK per year (230–11).

Measure	Stricter police enforcement of seat belt wearing among car passengers (ignition interlock device is assumed to ensure 100% use among drivers).
Target injuries	Injuries to unbelted car passengers.
Current number	14 fatalities and 215 injuries per year (based on Elvik (1997)).
Effect on injuries	25% reduction in probability of fatal injury when seat belts are worn. Wearing rate assumed to increase from 80 to 86% (Elvik, 1997).
Zero order effect	2.5 fatalities and 38 injuries prevented per year.
Implementation costs	60 million NOK in costs of additional enforcement per year (Elvik, 1997). Costs and effects occur in the same year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 18 million NOK per year.
Net effect on income	Net loss of 42 million NOK per year (60–18).

Measure	Stricter general police enforcement, targeted, for example, at respect for give way signs at junctions.
Target injuries	All injuries.
Current number	300 fatalities and 11 950 injuries per year.
Effect on injuries	Based on Elvik et al. (1997) a 5% reduction in the number of fatalities and a 2.5% reduction in the number of injuries have been assumed.
Zero order effect	15 fatalities and 290 injuries prevented per year.
Implementation costs	260 million NOK in costs of additional enforcement per year (Elvik, 1997). Costs and effects occur in the same year.
Income lost	No loss of income has been assumed to occur.
Income gained	Savings in accident costs of 129 million NOK per year.
Net effect on income	Net loss of 131 million NOK per year (260–129).

A.5. Estimate of combined effect of measures and marginal contribution of each measure

Let E_i denote the zero order effect of each measure in terms of the number of fatalities or injuries it prevents. Let R_i denote the residual of measure i, that is the number of fatalities or injuries it does not prevent. Both quantities are measured as proportions of the total number of fatalities or injuries. Thus, for the new speed limit system, including speed governors on cars, E_i is:

$$91/300 = 0.303,$$

and R_i is:

$$(300 - 91)/300 = 209/300 = 0.697.$$

Table A3 shows the zero order effects of each measure and the estimated values of R_i for each measure. The combined effect of all measures was estimated as:

$$\text{Combined effect} = \prod_{i=1}^{n} R_i$$

that is, as the product of the residuals of all 20 measures. The combined effect on fatalities estimated this way was a reduction of 211.5, whereas the sum of zero order effects was a reduction of 333.9.

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