A SYSTEMATIC COST-BENEFIT ANALYSIS OF 29 ROAD SAFETY MEASURES

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HIGHLIGHTS

- Cost-benefit analyses executed for 29 road safety measures
- Standardized data collection and assessment procedure
- Effects assessed of varying assumptions, including best and worst case scenarios
- 25 measures are cost-effective according to our best estimates

ABSTRACT

Economic evaluations of road safety measures are only rarely published in the scholarly literature. We collected and (re-)analyzed evidence in order to conduct cost-benefit analyses (CBAs) for 29 road safety measures. The information on crash costs was based on data from a survey in European countries. We applied a standardized procedure including corrections for inflation and Purchasing Power Parity in order to express all the monetary information in the same units (EUR, 2015). Cost-benefit analyses were done for measures with favorable estimated effects on road safety and for which relevant information on costs could be found. Results were assessed in terms of benefit-to-cost ratios and net present value. In order to account for some uncertainties, we carried out sensitivity analyses based on varying assumptions for costs of measures and measure effectiveness. Moreover we defined some combinations used as best case and worst case scenarios. In the best estimate scenario, 25 measures turn out to be cost-effective. 4 measures (road lighting, automatic barriers installation, area wide traffic calming and mandatory eyesight tests) are not cost-effective according to this scenario. In total, 14 measures remain cost-effective throughout all scenarios, whereas 10 other measures switch from cost-effective in the best case scenario to not cost-effective in the worst case scenario. For three measures insufficient information is available to calculate all scenarios. Two measures (automatic barriers installation and area wide traffic calming) even in the best case do not become cost-effective.

Inherent uncertainties tend to be present in the underlying data on costs of measures, effects and target groups. Results of CBAs are not necessarily generally valid or directly transferable to other settings.

1. INTRODUCTION

At the core of public policy, in road safety as well as in many other domains, is the challenge to identify how to use scarce resources to obtain the greatest possible benefits from them. Hauer (2011) provides two reasons why economic evaluations of road safety investments can be set up: 1) justify public money spending and 2) establish priority between projects. Several types of economic efficiency evaluation exist such as cost-effectiveness analysis (CEA), cost-utility analysis (CUA) and cost-benefit analysis (CBA) (Drummond et al., 2015). In road safety research, CBA has by far been the most popular tool. Although CBA has been severely criticized (Hauer, 2011), other authors have advocated its use (Rietveld, 2013; van Wee, 2011). Elvik (2001a) argues that the basic principles of cost-benefit analysis are in line with general principles of rational choice and thus cannot be rejected. Practice-oriented documents (AASHTO, 2010; PIARC, 2015) typically put forward economic evaluation including CBA as a method for ranking and prioritizing road safety measures.

To date, few economic evaluations of road safety measures have been published in the scholarly literature and few sources are available that provide a good overview on the current state of knowledge. Elvik (2003) examined how setting priorities according to cost-benefit analysis would affect the provision of road safety. Relying on policy analyses made in Norway and Sweden, he found that cost-effective road safety policies could prevent between 50 and 60% of the number of fatalities in both countries. A subsequent paper (Elvik, 2008) reported the benefit-to-cost ratios of 40 road safety measures in Norway for which cost-benefit analyses had been performed. Other reviews targeting economic evaluation studies of injury prevention were done by Polinder et al. (2012) who included among others 15 road safety measures, as well as by Yannis et al. (2008) who included 11 road safety measures. Other noteworthy sources of information about economic effects of road safety measures are Elvik et al. (2009) and its on-line successor (Høye et al., 2018), the latter unfortunately only available in Norwegian.

The present paper takes a bird-eye perspective and focuses on collecting and (re-)analyzing evidence in order to conduct cost-benefit analyses (CBAs) of road safety measures. The ultimate aim is to extend the knowledge base of the road safety domain with evidence on economic efficiency of measures as well as to present the information in such a way that the applied method and the results can be understood and used in future studies. The analyses were carried out within the SafetyCube project and the development of the European Road Safety Decision Support System (DSS), available at https://www.roadsafety-dss.eu.

The paper is structured as follows: section 2, 3 and 4 respectively describe the methodology, the data and the results. Section 5 complements the findings by presenting sensitivity analyses for each measure previously described. Finally, the results are discussed in section 6 and conclusions are drawn in section 7.

2. METHODOLOGY

2.1. Cost-benefit analysis

A cost-benefit analysis (CBA) of road safety measures allows the joint evaluation of the effectiveness of such measures in reducing crashes of different severity as well as to provide information on the socio-economic return of countermeasures. To that end a monetary value is assigned to each type of benefit that results from the measure. The aggregate value of these benefits (B) is compared to the costs (C) of the measure. In a CBA typically two outcomes are calculated:

(1) the net present value (NPV) = (B-C)

(2) the benefit-to-cost ratio (BCR) = (B/C)

Measures can be ranked or prioritized based on their NPV or BCR. In case of a positive NPV or a BCR equal to or higher than 1, a measure is cost-effective. CBA should only be done if B >0. In case the latter is not true, a measure is not effective and an efficiency analysis becomes meaningless.

When confined to road safety, the benefits represent the value of all crashes or injuries prevented by implementing the measure. Other possible (positive or negative) benefits are related to mobility and environmental impacts. Costs of a measure are one-time investment costs and recurrent costs.

The road safety benefits in period n, depending on the level of severity s, that result from the introduction of a measure, can then be calculated as follows.

$$Benefits_n = \sum_s Targetcrashes_s * Effectiveness_s * Crashcost_s$$

The **effectiveness of the measure** (Effectiveness) is typically expressed by means of the percentage reduction (PR) of either the number of crashes or the number of casualties as a consequence of the measure or by the Crash Modification Factor (CMF) (PR = 100*(1-CMF)). The effectiveness often varies according to the level of severity concerned.

The **target crashes** (Targetcrashes) are the number of crashes (or injuries) of various severity levels that possibly can be affected by the measure, so typically in before-after studies this is the estimated number of crashes in the before period corrected for regression to the mean and for trend effects.

The benefits can be expressed in monetary values by multiplying the number of prevented crashes or injuries with the monetary value of the benefit, i.e. the **cost per crash or injury** (Crashcost). Crash costs typically consist of several components of which human costs, i.e. immaterial costs, tend to be the most important (Wijnen & Stipdonk, 2016). Crash costs are strongly dependent on the severity level of the crash.

Subsequently, benefits (+) and costs (-) are expressed in their present value and summed up resulting in a net present value:

$$Net\ Present\ Value = \sum_{n=1}^{N} \frac{nominal\ value}{(1 + discount\ rate)^n}$$

With N = assumed lifespan of the measure (usually in years) and *nominal value* = the value in period n.

2.2. Harmonized crash cost estimates

In order to maintain comparability, we used the same values for crash costs across all the CBAs. The used values are the standardized cost figures that were reported by Wijnen et al. (2019). They used the framework of Alfaro et al. (1994) and did a survey among experts in 31 European countries about existing methods and data on official crash cost estimates, including details for different cost components across crash severity levels. All data were standardized for currency, inflation and for relative income differences (Purchasing Power Parity) between countries and eventually expressed in euros, 2015 values. For all but one countries, at least some information on costs of crashes appeared to be available. Reported costs vary between € 0.7 million and € 3.0 million per fatality. Reported costs per serious injury range from € 28,000 to € 959,000 and reported costs per slight injury range from € 296 to € 71,742. The total costs of crashes vary between 0.4% and 4.1% of the Gross Domestic Product (GDP). Not in all countries information is present for all cost components and/or all severity levels. Some countries for example exclude property damage only (PDO) crashes. Moreover, not all cost estimates are produced according to the same guidelines. Wijnen et al. (2019) applied a value transfer method to estimate standard cost values per casualty/crash type and to estimate the total costs of crashes for each European country that was included and for the EU28 in total. Basically, for each cost component, median values per casualty type (fatality, serious injury, slight injury), and per crash type (fatal, serious injury, slight injury and PDO) were determined, using data from countries that determined costs based on a Willingness-to-Pay (WTP) approach for the calculation of human cost. Applying the value transfer method to all cost components, the 'standard' costs of a fatality were estimated at €2.3 million. Costs per serious and slight injury were estimated at 13% and 1% of the value of a fatality. Detailed information can be found in Wijnen et al. (2019).

2.3. Calculation tool

A calculation tool (spreadsheet) was developed to execute all CBA analyses in a uniform way. Road safety evaluation studies typically either evaluate the effects on the number of crashes or the effects on the number of people involved in crashes of a certain severity level. The calculation tool allowed to conduct analyses based on preventing crashes as well as on preventing casualties. As road safety studies also often yield different reduction percentages according to the level of severity of the crash (typically expressed in the four categories 'crashes in which at least someone was killed' (F), 'crashes in which at least someone was seriously injured' (SE), 'crashes in which at least someone was slightly injured' (SL) and 'property damage only' (PDO) crashes), the tool was set up to enable the use of different reduction percentages for each crash severity category.

Values for the effectiveness (PR) and target crashes can be entered separately in the tool. The number of prevented crashes is calculated by multiplying the target group with the effectiveness. If no information on the size of the target group or the PR is available, the calculation tool also offers the possibility to directly enter the number of prevented crashes.

Monetary costs of measures typically consist of one-time implementation costs and annually recurrent costs. Annually recurrent costs were discounted to the price level of the reference year 2015. In case no distinction between implementation and annual costs could be made, total costs could be entered too.

All measure costs were updated to 2015 as a common reference year. Also the costs of crashes (thus the benefits in the CBA) were expressed at a common EUR 2015 level.

2.4. Analysis procedure

A stepwise procedure was followed for the selection of eligible road safety measures and for the subsequent analyses:

- Selection of measures that were meaningful candidates for a CBA. The measures were selected from an initial set of measures for which systematic information on their safety effects was collected. This set was based on a taxonomy of measures, covering road user, infrastructure, vehicle, and post-impact care measures (Martensen et al., 2018). The analysis method included a systematic literature search strategy, a template for coding key data from individual studies and guidelines for summarizing the findings (Martensen et al., 2018). For every selected measure a 'synopsis' document was created, synthesizing the coded studies and outlining the main findings in the form of a meta-analysis (where possible) or another type of comprehensive synthesis (e.g. vote-count analysis). These synopses can be consulted on https://www.roadsafety-dss.eu/#/measure-search.

- For the purpose of executing economic evaluation, only measures with favorable estimated effects on road safety were selected.
- For all the measures information was sought on 3 variables:
    1. Costs of the measure
    2. Effectiveness of the measure in terms of crash or casualty reduction
    3. Information on the number, nature and severity of affected crashes
- Information on costs of a measure could either come from a scholarly published source or a source in grey literature that was considered to be sufficiently reliable, e.g. from government reports.
- Information on effectiveness of a measure as well as information on the number and the nature of the affected crashes (i.e. the target group) preferably had to come from a peer-reviewed journal, if possible a meta-analysis.
- In order to maintain comparability, the EU standard crash cost values (see 2.2) were applied in all the executed cost-benefit analyses.

Using this information, the economic efficiency of the measure was calculated in terms of the NPV per unit of the measure and the BCR.

3. INPUT DATA

Table 1 gives an overview of the included measures and explains the nature and the scope of the measure concerned. The measures are structured in six categories: infrastructure (13 measures), legislation (1), enforcement (6), education (4), post-crash treatment (1) and vehicle equipment (4). For each measure information is given in Table 2 on the chosen unit of analysis, the assumed time horizon (= lifetime of the measure), the costs, the used effect estimates and the target crashes used to execute the CBA. Table 2 also provides the references used for the information on the costs of the measure, the effects and the target number of crashes or casualties. Furthermore, it is indicated whether the available effect information is based on either a single study or a meta-analysis.

Table 1: Included measures

Measure	Description
Infrastructure	
High risk sites treatment	Identification and treatment of locations with an elevated crash risk (intersections or road sections)
Dynamic speed limits	Limits that change according to real-time traffic, road or weather conditions
Installation of speed humps	Vertical speed deflection devices, aim to reduce vehicle speeds, particularly in urban and residential areas.
30 km/h zones	Implementation of 30 km/h zones
Road lighting	Installation of road lighting on unlit roads
Rumble strips at centreline	Raised pavement markers placed along a road's centreline
Chevron signs	Safety devices to warn drivers of the severity of a curve by delineating the alignment of the road around that curve
Channelisation	Installation of left turn lanes at crossroads
Automatic barriers at rail-road crossings	Automatic barriers instead of level crossings
Area wide traffic calming	Implementation of speed reducing measures (speed humps, chicanes…) in an area
Safety barriers	Roadside barriers, containing vehicles and redirecting them back to the carriageway (installation or type change)
Roundabouts	Conversion of junctions to roundabouts
Traffic signals	Traffic signal installation
Legislation	
Mandatory eyesight tests	Mandatory visual acuity tests for drivers above 45 (to be retaken every 10 years) and a treatment (glasses) for those who fail and can be treated
Enforcement	
Enforcement of seat-belt wearing for light-vehicle occupants	Increased police checks on seat-bealt wearing
Alcohol Interlock Program	Compulsory alcohol interlock program for serious offenders. Alcohol interlocks are automatic control systems which are designed to prevent driving with excess alcohol by requiring the driver to blow into an in-car breathalyzer before starting the ignition.
Red light cameras	Red light enforcement cameras
Random breath tests	Random breath tests to detect drunk driving
Section control	Speed enforcement scheme in which cameras measure average speeds over a longer road section
Police enforcement of speeding	Checking and penalizing drivers who exceed speed limits by means of police enforcement
Education	
Child pedestrian training	Education and training for children (-12Y) in pedestrian skills
Seatbelts campaign combined with enforcement	Awareness raising campaign to improve seat-belt use combined with increased enforcement
Drink-driving advertising campaign	Advertising campaign tackling drink-driving among drivers
Booster seat program	A variety of single activities targeted at children, parents or physicians such as strategy development, community education, newspaper articles, website and newsletter, brochures, flyers, radio and TV public service announcements, discount coupons and citizen advisory groups
Post-crash treatment	
Ambulance helicopters	Helicopters for ambulance missions in sparsely populated areas
Vehicle equipment	
Child restraints	Belts, seats,... to restrain children in cars

Measure	Description
Electronic Stability Control	Technology that improves a vehicle's stability by detecting and reducing loss of traction
Autonomous Emergency Braking	Automobile braking technology that warns the driver when there is a danger of collision with a forward obstacle and that controls the brakes when a collision is judged imminent or unavoidable
ABS for PTW	Antilock Braking Systems (ABS) for Powered Two Wheelers (PTW)

The **unit of analysis** for the CBAs represents the dimensions of the area for which the CBA was executed. Seven possible units of intervention occurred:

- One location, e.g. an intersection, a curve or a crossing. This was for instance used in the CBAs for high risk site treatment or conversion into a roundabout.
- A road segment where a measure is implemented, often expressed in km. Examples are the installation of a section control system or dynamic speed limits.
- An 'area' of undefined size, often a neighborhood or some streets that have undergone a similar treatment. Examples of these can be found in the CBAs for 30 km/h zones and area-wide traffic calming.
- A person, e.g. a driver that was tested for driving under the influence of alcohol or a participant in an education program.
- A vehicle, e.g. a car or a motorcycle, which is the typical unit used for all vehicle measures.
- A jurisdiction (typically a country or a state) in which a certain measure is applied, e.g. a campaign, a law, an enforcement policy...)
- An intervention in which a certain action is taken, e.g. a helicopter intervention.

The **time horizon** is the expected lifetime of the measure. For many measures in the area of road infrastructure a time horizon of 25 years seems realistic (Elvik et al., 2009). In line with other studies, an average vehicle lifetime of 14 years was assumed (EC, 2006). For some measures, often those that are more technology-related (e.g. red-light cameras) or those that are more subject to wearing out (e.g. rumble strips), a shorter horizon was taken at the discretion of the authors. For educational measures a lifetime of 1 year was assumed.

Information on costs of **measures** was sought in various sources. These costs are typically subject to large variations and are usually poorly documented in existing studies and publicly available sources. Priority was given to estimates from the most reliable sources, which were considered to be peer-reviewed articles, but also research reports. Furthermore, preference was given to the more recent estimates (as compared to older estimates). Table 2 lists the sources used for the measure cost for each measure. The table also presents an overview of the estimates of the annually recurrent costs of the selected measures. To make a proper comparison possible, all measure costs are expressed in euro and are converted to average EU-28 PPP (Purchasing Power Parity) values for 2015.

The minimum requirement for conducting a CBA was that at least one sufficiently reliable effectiveness evaluation study was available that provided a quantitative estimate of the **safety effect**. Studies that met the criterion of sufficient reliability were studies published in the peer-reviewed literature, the studies published in Elvik et al. (2009) as well as in Høye et al. (2018) and in a few cases also research reports published by governmental organizations. Ideally a meta-analysis of the safety effect of the measure should be available in the literature. If a meta-analysis was not available, the information on effectiveness was retrieved from one of the existing studies, in principle from the one with the highest reliability, i.e. the strongest methodological rigor or the highest number of observations. An additional criterion was whether the study applied to a relevant context with respect to the costs of the measure. For example, if cost estimates were only available for a measure in urban traffic, then an effect study was looked for that was done in urban traffic as well.

Cost estimates in general tend to be rather weakly documented and only sparsely available. Even in the best cases, only a few cost estimates were available. In those cases, priority was given to the most recent estimates, the ones that were most applicable to the European situation and the ones that came from the most reliable sources (e.g. from peer-reviewed articles).

Table 2 also includes the lower and upper limits of the 95% confidence intervals (CI) for the effects of the selected measures. The 95% CI of the effect estimates were used to quantify the level of uncertainty of the effects.

Finally, Table 2 presents the number of **target crashes** as used in the CBA including the source of these data. The information on target group crashes was ideally retrieved from the same reference as the effectiveness evaluation.

A discount rate of 2.5% was used in all calculations.

Table 2: Input data

Measure	Unit of analysis	Time horizon (in years)	Investment cost *	Annual costs *	Total discounted costs *	Source cost information (EU⌂)	Annual effect during measure lifetime Best estimate	Annual effect during measure lifetime Low measure effect	Annual effect during measure lifetime High measure effect	Source effect information	Study type ***	Target crashes/users type	Annual target crash number or target injury number per unit of analysis	Source target crash information
Infrastructure														
High risk sites treatment	1 intersection	25	€ 21 446	€ 1 960	€ 57 558	Høye et al. (2018)	CR (F, SE, SL, PDO): 28%	CR (F, SE, SL, PDO): 23%	CR (F, SE, SL, PDO): 32%	Høye et al. (2018) (INT⌂)	MA (26 studies)	All crashes	NC (F, SE, SL): 1.37; NC (PDO): 3.38	Meuleners et al. (2008) (AU⌂)
Dynamic speed limits	1 highway km	25	€ 311 070	€ 9 722	€ 490 192	De Pauw et al. (2017)	CR (F, SE): 6%; CR (SL): 18%; CR (PDO): 18% (°)	CR (F, SE): -29%(°°); CR (SL): 4%; CR (PDO): 4% (°)	CR (F,SE): 32%; CR (SL): 30%; CR (PDO): 30% (°)	De Pauw et al. (2017) (BE⌂)	SS (59.5 km motorway)	All crashes	NC (F): 0.045; NC (SE): 0.402; NC (SL): 1.608; NC (PDO): 9.797	De Pauw et al. (2017) (BE⌂)
Installation of speed humps	1 speed hump	25	€ 3 189	-	€ 3 189	Yannis et al. (2005)	CR (F, SE, SL): 17%	CR (F, SE, SL): 8%	CR (F, SE, SL): 25%	Høye et al. (2018) (INT⌂)	MA (13 studies)	All crashes	NC (F, SE, SL): 0.184	Yannis et al. (2005) (GR⌂)
30 km/h zones	1 area of undefined size	25	€ 90 478	€ 1 199	€ 112 572	Peters & Anderson (2013)	CR (F): 57%; CR (SE): 26%; CR (SL): 22%	CR(F): 17.2%; CR (SE): 14.4%; CR (SL): 13.7%	CR (F): 95.8%; CR (SE): 38.1%; CR (SL): 29.6%	Peters & Anderson (2013) (GB⌂)	SS (399 zones)	All crashes	INJ (F): 0.006, INJ (SE): 0.039, INJ (SL): 0.374	Peters & Anderson (2013) (GB⌂)
Road lighting	1km of roads	25	€ 42 480	€ 2 360	€ 85 962	Høye et al. (2018)	CR (F): 52%; CR (SE, SL): 26%	CR (F): 45%; CR (SE, SL): 19%	CR (F): 59%; CR (SE, SL): 33%	Høye et al. (2018) (INT⌂)	MA (49 studies)	Nighttime crashes	NC (F, SE, SL): 0.105	Steinbach et al. (2015) (GB⌂)
Rumble strips at centreline	1km of roads	10	€ 987	€ 0	€ 987	Lyon et al. (2015)	CR (F, SE, SL, PDO): 37%	CR (F, SE, SL, PDO): 31%	CR (F, SE, SL, PDO): 42%	Høye et al. (2018) (INT⌂)	MA (17 studies)	Head-on crashes, crashes with run-off-the-road to the left, sideswipe-crashes with vehicle in the left-hand side oncoming lane	NC (F, SE, SL): 0.021 ; NC (PDO): 0.047	Lyon et al. (2015) (US⌂)
Chevron signs	1 curve	10	€ 429	€ 9	€ 508	Høye et al. (2018)	CR (F, SE, SL, PDO): 2.6%	CR (F, SE, SL, PDO): -48.3% (°°)	CR (F, SE, SL, PDO): 53.6%	Montella (2009) (IT⌂)	SS (15 curves)	All crashes	NC (F, SE, SL): 0.047; NC (PDO): 0.1	Montella (2009) (IT⌂)

Measure	Unit of analysis	Time horizon (in years)	Investment cost *	Annual costs *	Total discounted costs *	Source cost information (EU⌂)	Annual effect during measure lifetime Best estimate	Annual effect during measure lifetime Low measure effect	Annual effect during measure lifetime High measure effect	Source effect information	Study type ***	Target crashes/users type	Annual target crash number or target injury number per unit of analysis	Source target crash information
Channelisation	1 intersection	25	€ 150 000	€ 2 500	€ 196 061	Elvik et al. (2009)	CR (F, SE, SL, PDO): 27%	CR (F, SE, SL, PDO): 4%	CR (F, SE, SL, PDO): 45%	Høye et al. (2018) (INT⌂)	MA (48 studies)	All crashes	NC: 2.7	Newstead & Corben (2001) (AUS⌂)
Automatic barriers at rail-road crossings	1 crossing	25	€ 135 000	€ 4 000	€ 208 698	Elvik et al. (2009)	CR (F, SE, SL, PDO): 68%	CR (F, SE, SL, PDO): 57%	CR (F, SE, SL, PDO): 76%	Elvik et al. (2009) (INT⌂)	MA (17 studies)	All crashes	NC (F, SE, SL, PDO): 0.007	European Railway Agency (2012) (EU⌂)
Area wide traffic calming	1 area	25	€ 5 389 225		€ 5 389 225	Yannis et al. (2005)	CR (F, SE, SL): 15%; CR (PDO) (°): 15%	CR (F, SE, SL): 12%; CR (PDO) (°): 12%	CR (F, SE, SL): 17%; CR (PDO) (°): 19%	Elvik, (2001b) (INT⌂)	MA (33 studies)	All crashes	NC (F, SE, SL): 1.4 ; NC (PDO): 10	Yannis et al. (2005) (GR⌂)
Safety barriers	1 km rural road	25	€ 39 070	€ 1 804	€ 72 314	Elvik et al. (2009)	CR (F): 46%; CR (SE): 55%; CR (SL): 55%; CR (PDO): -100% (°°)	CR (F): 12%; CR (SE): 42%; CR (SL): 42%; CR (PDO): -100% (°°)	CR (F): 67%; CR (SE): 65%; CR (SL): 65%; CR (PDO): -100% (°°)	Høye et al. (2018) (INT⌂)	MA (36 studies)	All crashes	NC (F): 0.0283; NC (SE): 0.1357; NC (SL): 0.9413; NC (PDO): 0.6054	EC (2016) + CARE database/Date of query: September 2017 (EU⌂)
Roundabouts	1 intersection	25	€ 363 000	€ 5 000	€ 455 122	Pokorný (2011)	CR (F): 72% CR (SE, SL): 47% CR (PDO): 0%	CR (F): 42%; CR CR (SE, SL): 41%; CR (PDO): -15%(°°)	CR (F): 86%; CR (SE, SL): 52%; CR (PDO): 17%	Elvik, R. (2017) (INT⌂)	MA (44 studies)	All crashes	NC (F, SE, SL, PDO): 5.9	Flannery & Elefteriadou, (1999) (US⌂)
Traffic signals	1 intersection	25	€ 48 309	€ 3 370	€ 98 285	Elvik et al. (2009)	CR (F, SE, SL, PDO): 29%	CR (F, SE, SL, PDO): 14%	CR (F, SE, SL, PDO): 41%	Høye et al. (2018) (INT⌂)	MA (4 studies)	All crashes	NC (F, SE, SL): 0.3031; NC (PDO): 0.1541	Jensen & ApS (2009) (DK⌂)
Legislation														
Mandatory eyesight tests	1 driver	1			€ 47	Vlakveld et al. (2005)	at country level (NO⌂): Prevented F: 0.49 ; Prevented INJ (SE or SL): 20.6; Prevented NC (PDO): 152			Vaa (2003) (INT⌂)	MA (22 studies)	See effect information	See effect information	Vlakveld et al. (2005) (NO⌂)
Enforcement														
Enforcement of seat-belt wearing for light-vehicle occupants	1 country	1			€ 5 173 139	Elvik (2010)	PR before: 94% PR after: 96% By use of seat belt: IR (F): 60%; IR (SE, SL): 44%	PR before: 94% PR after: 96% By use of seat belt: IR (F): 53%; IR (SE, SL): 27%	PR before: 94% PR after: 96% By use of seat belt: IR (F): 66%; IR (SE,SL): 58%	Høye, A. (2016a) (INT⌂)	MA (16 studies for effect on seat-belt use; 22 studies effect in crashes)	Occupants of light vehicles	INJ (F): 75; INJ (SE): 308; INJ (SL) : 2982	Statistics Norway, 2015 (NO⌂)

Measure	Unit of analysis	Time horizon (in years)	Investment cost *	Annual costs *	Total discounted costs *	Source cost information (EU[⌂])	Annual effect during measure lifetime Best estimate	Annual effect during measure lifetime Low measure effect	Annual effect during measure lifetime High measure effect	Source effect information	Study type ***	Target crashes/users type	Annual target crash number or target injury number per unit of analysis	Source target crash information
Alcohol Interlock Program	1 participant	2		€ 1 534		SWOV (2009)	At country level (NL[⌂]): Prevented F: 2.8; Prevented SE: 72.7; Prevented SL: 1125; Prevented NC (PDO): 3988.3	At country level (NL[⌂]): Prevented F: 2.0; Prevented SE: 52.3; Prevented SL: 810; Prevented NC (PDO): 2871.6	At country level (NL[⌂]): Prevented F: 3.1; Prevented SE: 79.4; Prevented SL: 1230; Prevented NC (PDO): 4360.5	Elder et al. (2011) (INT[⌂])	MA (9 studies)	alcohol-related crashes	See effect information	SWOV (2009) (NL[⌂])
Red light cameras	1 intersection	10	€ 84 000	€ 2 900		Daniels et al. (2017)	CR (F, SE, SL): 12%; CR (PDO): -3% (°°)	CR (F, SE, SL): -5% (°°) CR (PDO): -53% (°°)	CR (F, SE, SL): 27% PDO CR: 31%	Høye, (2013) (INT[⌂])	MA (30 studies)	all crashes	INJ (F, SE, SL): 3.06; PDO: 21.34	De Pauw et al. (2014) (BE[⌂])
Random breath tests	1 tesst	1			€ 32.84	Mackay et al. (2003)	CR (F, SE, SL, PDO): 14%	CR (F, SE, SL, PDO): 11%	CR (F, SE, SL, PDO): 18%	Elvik et al. (2009) (INT[⌂])	MA (40 studies)	alcohol-related crashes	NC: 0.0152/	Mackay et al. (2003) (AU[⌂])
Section control	1 highway km	15	€ 68 323	€ 6 832	€ 152 913	Owen et al. (2016)	CR (F, SE): 56%; CR (SL, PDO): 30%	CR (F, SE): 42%; CR (SL, PDO): 24%	CR (F, SE): 66%; CR (SL, PDO): 36%	Høye, A. (2014) (INT[⌂])	MA (4 studies)	All crashes	NC (F): 0.08; NC (SE): 0.60; NC (SL): 0.45; NC (PDO): 2.41	Montella et al. (2012) (IT[⌂])
Police enforcement of speeding	1 area	1			€ 1 171 376	Goldenbeld & van Schagen (2005)	CR (F, SE, SL, PDO): 18%	CR (F, SE, SL, PDO): 13%	CR (F, SE, SL, PDO): 23%	Erke et al. (2009) (INT[⌂])	MA (45 studies)	All crashes	NC (F, SE, SL): 47.6; NC (PDO): 346.15 (°°°)	Goldenbeld & van Schagen (2005) (NL[⌂])
Education														
Child pedestrian training	1 state	1			€ 574 689	NCHRP (2008)	CR (F, SE, SL): 12%			Blomberg et al. (1983) (US[⌂])	SS (road-side observations in 3 cities)	Crashes with primary school-aged children (6-12) as pedestrians	NC (F): 1.82 NC (SE, SL): 140.51	NCHRP (2008) (US[⌂])
Seatbelts campaign combined with enforcement	1 country	1			€ 468 832	Tamis K. (2009)	IR (F): 60%; IR (SE,SL): 44% PR before : 93,8% PR after: 95,6%	IR (F): 53%; IR (SE,SL): 27% PR before: 93,8% PR after: 95,6%	IR (F): 66%; IR (SE, SL): 58% PR before: 93,8% PR after: 95,6%	Tamis, K. (2009) (NL[⌂]) Høye, A. (2016a) (INT[⌂])	SS (road-side observations 25 locations)	Car occupants	INJ (F): 214; INJ (SE): 2 832 INJ (SL)°: 91128	Tamis, K. (2009) (NL[⌂])
Drink-driving advertising campaign	1 state	1			€ 862 157	Murry et al. (1996)	Prevented: NC (F, SE): 15.4; NC (PDO): 112 (°°°)			Murry et al. (1996) (US[⌂])	SS (accidents in 3 cities	crashes of 18-24-year-old males	See effect information	Murry et al. (1996) (US[⌂])

Measure	Unit of analysis	Time horizon (in years)	Investment cost *	Annual costs *	Total discounted costs *	Source cost information (EU⌂)	Annual effect during measure lifetime Best estimate	Annual effect during measure lifetime Low measure effect	Annual effect during measure lifetime High measure effect	Source effect information	Study type ***	Target crashes/users type	Annual target crash number or target injury number per unit of analysis	Source target crash information
Booster seat program	1 state	1			€ 463 980	NCHRP (2008)	CR (F, SE, SL): 8%	(CR (F, SE, SL): 2%	CR (F, SE, SL): 10%	Durbin et al. (2003) (injury effect) (US⌂) and NCHRP (2008) (usage) (US⌂)	Effects on injuries: SS (3616 crashes); Effects on usage: MA (4 studies)	Crashes with child (4-8y) occupants	NC (F): 3.86; NC (SE, SL): 298	NCHRP (2008) (US⌂)
Post-crash treatment														
Ambulance helicopters	1 helicopter intervention	1			€ 13 826	Elvik (2002)	Prevented: INJ (F): 0.06; INJ (SE): 0.2	Prevented: INJ (F): 0.02; INJ (SE): 0.1	Prevented: INJ (F): 0.10; INJ (SE): 0.3	Elvik (2002) (NO⌂)	SS (730 interventions)	Crashes with helicopter intervention	See effect information	Elvik (2002) (NO⌂)
Vehicle equipment														
Child restraints	1 car	4			€ 214	Elvik et al. (2009)	IR (F): 81% IR (SE): 69% IR (SL): 25% (correctly used restraint vs. no restraint)	IR (F): 57% IR (SE): 64% IR (SL): 16% (correctly used restraint vs. no restraint)	IR (F): 92% IR (SE): 73% IR (SL): 32% (correctly used restraint vs. no restraint)	Høye et al. (2018) (INT⌂)	MA (29 studies)	vehicle crashes with at least one occupant in age category 0-10 years	prevented INJ (F): 47; INJ (SE): 99; INJ (SL): 396	Høye et al. (2018) (NO⌂)
Electronic Stability Control	1 car	14			€ 147	Baum et al. (2007)	CR(F) : 26% CR (SE, SL) : 2%	CR(F) : 19% CR (SE, SL) : -2% (°°)	CR(F) : 33% CR (SE, SL) : 5%	Høye et al. (2018) (INT⌂)	MA (20 studies)	Crashes involving cars	NC (F): $7.00*10^{-5}$ NC (SE, SL): $349.95*10^{-5}$ NC (PDO): $34300*10^{-5}$	EU-CARE (2018) (EU)
Autonomous Emergency Braking	1 car	14			€ 217	NHTSA (2012)	CR (F): 5.3% CR (SE, SL, PDO): 16%	CR (F): 5.3% CR (SE, SL, PDO): -6% (°°)	CR (F): 5.3% CR (SE, SL, PDO): 34%	Høye et al. (2015) (INT⌂)	MA (23 studies)	All crashes	NC (F): $8.03*10^{-5}$ NC (SE, SL): $401.31*10^{-5}$ NC (PDO): $39334*10^{-5}$	EU-CARE (2018) (EU)
ABS for PTW	1 motorcycle	13			€ 400	Andersson et al. (2011)	CR (F, SE, SL, PDO): 29%	CR (F, SE, SL, PDO): 24%	CR (F, SE, SL, PDO): 35%	Høye, A. (2016b) (INT⌂)	MA (6 studies)	Crashes with motorcyclists	NC (F): $12.79*10^{-5}$ NC (SE): $160.01*10^{-5}$ NC (SL): $860.08*10^{-5}$	EU-CARE (2018) (EU)

⌂ INT= information based on multiple countries (meta-analysis); EU= European Union; Used country abbreviations (ISO): AU= Australia; BE= Belgium; DK= Denmark; GB= United Kingdom of Great Britain and Northern Ireland; GR= Greece; IT= Italy; NL= Netherlands; NO= Norway, US= United States of America.

* All costs are expressed per unit of analysis, in EUR EU-28 PPP (2015)

** NC = number of crashes; INJ = number of injuries; CR = reduction in the number of crashes; IR= reduction in the number of injuries; F= Fatal injury; SE = Serious injury; SL = Slight injury; PDO = Property Damage Only; PR = Penetration Rate; e.g. NC (F) = number of fatal crashes, CR (SE, SL) = reduction of the number of crashes with serious or slight injuries; NC (F, SE, SL) = number of crashes with at least someone injured;

*** MA = meta-analysis; SS = single study; followed by the number of studies (MA) or cases (measurement unit always indicated) (SS) between parentheses

(°) Extrapolation

(°°) Negative values = expected increase in number of crashes /injuries

(°°°) Number of PDO crashes estimated by using general proportion of PDO versus all injury crashes

4. RESULTS

In total CBAs were executed for 29 different measures. Two outcome values were calculated for all the selected measures: the benefit-to-cost ratio (BCR) and the net present value (NPV) of the effects per unit of the measure. The results are provided in Table 3. All the monetary values are expressed in euro (price level 2015, PPP EU-28). A BCR of 1 reflects the situation in which benefits equal costs. BCR values above 1 indicate a favorable benefit-to-cost ratio while BCR values below 1 reflect a situation in which the measure benefits (in terms of the monetary value of the reduced number of crashes) do not cover the measure costs. 25 measures have a BCR ≥1 and thus are cost-effective according to our best estimate. Four measures (road lighting, automatic barriers installation, area wide traffic calming and mandatory eyesight tests) have an estimated BCR between 0 and 1. This means that these measures are *effective* (they reduce the number of injuries or crashes), but not *cost-effective* (they come at a cost that is higher than the resulting benefits). Table 3 also includes the NPV of each measure. All NPV are calculated per unit of analysis. In case of a BCR below 1 the NPV becomes negative by definition as the estimated costs exceed the benefits. Although NPV and BCR point in the same direction, their meaning is different. In order to see the difference between the rankings by using NPV and BCR, it is interesting to compare the results for 'high risk sites treatment' and 'channelization', both applicable to intersections. Although the benefit-to-cost ratio for channelization (8.4) is lower than the one for high risk sites treatment (16.1), channelization results in a higher net present value (1 452 858 €) as compared with high risk site treatment (869 825 €). This seeming contradiction results from the fact that a ratio does not account for the scale of a measure. Channelization has a very high cost but an even higher benefit. As both – costs and benefits – are large numbers, the difference between the two is very large, even if the ratio of benefits and costs is actually smaller than that for high risk site treatment, where both the costs and as the benefits are smaller. From a pure economic perspective NPV is to be preferred over BCR as it shows how much a measure contributes to overall welfare. Finally, the BCR in some cases can become negative too. This situation only occurs in case of measures with negative benefits, which in the current study only occurs in the case of a 'low measure effect', i.e. in case one assumes that the effect of the measure is at the lower limit of the 95% confidence interval. Finally one can also compute break-even values for the different measures. This can be done by simply adding up the values of the total discounted costs (Table 2) and the NPV per unit implemented (Table 3). For example: the break-even cost of road lighting is 85 962 € - 24 888 € = 61 074€.

Table 3: B/C ratio's and Net Present Values per unit for all the selected measures

Measure	B/C ratio Best estimate	NPV per unit implemented	B/C ratio Low measure effect	B/C ratio High measure effect	B/C ratio Low measure cost (-50%)	B/C ratio High measure cost (+100%)	B/C ratio Worst case	B/C ratio Best case
Infrastructure								
High risk sites treatment	16.1	€ 869 825	13.2	18.4	32.2	8.1	6.6	36.8
Dynamic speed limits	1.1	€ 31 548	-2.3	3.6	2.1	0.5	-1.2	7.2
Installation of speed humps	18.2	€ 66 138	8.6	26.8	36.4	9.1	4.3	53.8
Implementation of 30 km/h zones	2.1	€ 128 619	0.9	3.4	4.3	1.1	0.4	6.7
Road lighting	0.7	-€ 24 888	0.5	0.9	1.4	0.4	0.3	1.8
Implementation of rumble strips at centreline	9.1	€ 7 950	7.6	10.3	18.1	4.5	3.8	20.5
Installation of chevron signs	2.7	€ 881	-50.8	56.4	5.5	1.4	-25.4	112.8
Channelisation	8.4	€ 1 452 858	1.2	14.0	16.8	4.2	0.6	28.0
Automatic barriers installation	0.05	-€ 198 049	0.04	0.06	0.11	0.03	0.02	0.12
Area wide traffic calming	0.1	-€ 4 810 007	0.1	0.1	0.2	0.1	0.0	0.2
Safety barriers installation; Change type of safety barriers	19.5	€ 1 339 933	10.6	25.4	39.1	9.8	5.3	21.2
Roundabouts	9.2	€ 3 749 171	8.1	10.2	18.5	4.6	4.0	20.4
Traffic signal installation	1.1	€ 8731	0.5	1.5	2.2	0.5	0.3	3.1
Legislation								
Mandatory eyesight tests	0.5	€ -23			1.5	0.3		

Measure	B/C ratio Best estimate	NPV per unit implemented	B/C ratio Low measure effect	B/C ratio High measure effect	B/C ratio Low measure cost (-50%)	B/C ratio High measure cost (+100%)	B/C ratio Worst case	B/C ratio Best case
Enforcement								
Enforcement of seat-belt wearing for light-vehicle occupants	28.7	€ 143 348 096	17.7	42.9	57.4	14.4	8.8	85.8
Alcohol Interlock Program	10.9	€ 29 174	7.8	11.9	21.7	5.4	3.9	23.8
Red light cameras	3.7	€ 282 577	-5.6	11.1	7.3	1.8	-2.8	22.2
Random breath tests	7.7	€ 219	6.0	9.9	15.4	3.8	3.0	19.7
Section control	19.5	€ 2 834 895	14.7	23.0	39.1	9.8	7.3	46.1
Police enforcement of speeding	1.1	€ 84 271	0.8	1.4	2.1	0.5	0.4	2.7
Education								
Child pedestrian training	2.6	€ 935 422			5.3	1.3		
Seatbelts campaign combined with enforcement	69.8	€ 32 272 145	42.2	105.6	139.7	34.9	21.1	211.1
Drink-driving advertising campaign	2.1	€ 932 113			4.2	1.0		
Booster seat program	4.6	€ 1 671 196	1.2	5.8	9.2	2.3	0.6	11.5
Post-crash treatment								
Ambulance helicopters	9.9	€ 123 372	3.4	16.4	19.8	5.0	1.7	32.8
Vehicle equipment								
Child restraints	3.4	€ 503	2.5	3.8	6.7	1.7	1.3	7.5

Measure	B/C ratio Best estimate	NPV per unit implemented	B/C ratio Low measure effect	B/C ratio High measure effect	B/C ratio Low measure cost (-50%)	B/C ratio High measure cost (+100%)	B/C ratio Worst case	B/C ratio Best case
Electronic Stability Control	4.4	€ 497	3.4	5.4	8.8	3.3	1.5	12.8
Autonomous Emergency Braking	4.8	€ 812	-1.0	9.5	9.5	2.4	-0.5	18.9
ABS for PTW	9	€ 3 183	7.1	10.9	17.9	4.5	3.6	21.7

5. SENSITIVITY ANALYSES

In order to assess how possible changes in underlying assumptions can influence the CBA results, we ran three sorts of sensitivity analyses. Firstly, we checked the consequences of scenarios in which the effects of the measures are lower or higher than initially expected. Secondly, we did the same for scenarios with varying costs of measures. Thirdly we combined the sensitivity analyses on costs and effects to calculate two 'extreme' scenarios. The scenarios are explained and discussed below.

5.1. Lower and higher effects

First, we assessed the consequences of varying effect estimates. If available, we used the upper and lower limits of the 95% confidence intervals of the estimates. In the ideal case these estimates were resulting from a meta-analysis, in other cases the used values result from one or two particular studies. The used values represent a (much) lower than expected and a (much) higher than expected effect respectively. Table 3 presents the results. For reasons of simplicity only BCR and no NPV values are presented for all the sensitivity analyses. For 10 measures, the low-effect scenario results in a BCR below 1, for 16 measures the BCR remains above 1 even if the effect is at the lower limit of the 95% confidence interval. For 3 measures no confidence interval of the results was available.

5.2. Lower and higher costs

Costs of measures are generally poorly known. The sources of these estimates and their rigor are sometimes unclear. Other estimates are rather old. Some of the estimates may only apply to very particular conditions. When it comes to infrastructural measures variables such as road type, traffic volume, number of lanes, land use conditions etc., are likely to play an important role. Huge variations therefore tend to exist. These huge variations are an important source of uncertainty that is as large as the uncertainty about the effect estimates. Logically, also the scenarios for the measure costs should clearly reflect the inherent uncertainties of the analyses. However, in contrast to the effect estimates that are for some measures relatively well established and formally assessed, this is not at all the case for the costs of measures. For most cases only one or two estimates for the costs of the measures were available, which does not allow a formal estimate of uncertainty by assessing the variation of the estimates. In order to reflect the inherent uncertainty of cost estimates we decided to include also two scenarios in which the measure costs vary from a ‘very low’ (-50% of the estimate) level to a ‘very high’ (+ 100% of the best estimate) level. These threshold values are to a certain extent arbitrary, but they are believed to reflect realistic boundaries for different reasons described below.

In many cases there are good reasons to presume that the current cost estimates are rather low. Many estimates tend to include only direct ‘out-of-pocket’ costs, e.g. based on payments to contractors, while other costs such as administrative costs for preparation, installation and maintenance or overhead costs are not included. It is therefore more likely that real costs will be underestimated rather than overestimated. This explains the choice of the + 100% upper limit and also the skewness of the used interval [-50%; +100%]. However, although somewhat less likely, costs can also be overestimated. For instance for technology-based measures, decreasing costs of technology due to mass production, innovation, competition, efficiency improvements etc. might lead to substantial reductions of the costs of a measure, so there is a good reason not just to look at cost increases. For example, Owen et al. (2016) have argued that ‘permanent average speed camera sites were estimated to have cost up to 1.5 million GBP per mile in 2000 but in 2016 cost an average of 100,000 GBP per mile’.

The results are provided in Table 3. Measures such as dynamic speed limits or the installation of traffic signals are clearly sensitive to changes in the costs of measures as their BCR values change from above 1 to below 1 from the low to the high cost scenarios.

5.3. A worst case and a best case scenario

Finally, we define two rather extreme scenarios:

- **a ‘worst case’ scenario** as a combination of a much worse than expected effect (the lower limit of the 95% confidence interval of the effect estimate) and a higher than expected measure cost (i.e. the estimated cost +100%).

- **a 'best case' scenario** that is a combination of a much better than expected effect (upper limit of the 95% CI of the effect estimate) and a lower than expected measure cost (estimated cost - 50%).

The results of the CBA for these scenarios are reflected in Table 3. For three measures, insufficient information was available to calculate worst-case and best-case scenarios.

In total, 14 measures remain cost-effective, in the best case as well as in the worst-case scenario, whereas 10 other measures (e.g. 30 km/h zones or traffic signal installations) switch from cost-effective to not cost-effective. Two measures (automatic barriers installation and area wide traffic calming) do not even become cost-effective in the best case.

6. DISCUSSION

6.1. Standardized approach

The main objective of the present work was to set up a standardized approach for economic efficiency evaluation by means of CBA for typical road safety measures. We standardized crash costs, we normalized all input data for inflation rates and purchasing power parity and subsequently applied the same calculation procedure for the 29 selected measures in order to calculate outcome measures (BCR & NPV) per unit of implementation. This standardized approach is the main asset of the present study as it allows a comparison between the outcomes of various measures that is at least not confounded by factors like differences in reference year, welfare level or currency exchange rates. A practical consequence of the standardized approach is that the obtained BCRs as reflected in Table 3 often differ from the ratios that were reported in the underlying studies.

6.2. Measures selected

When selecting eligible measures to assess, we tried to adopt a systematic approach as explained in section 2.4. The resulting list is inevitably incomplete. Moreover, the composition of the list might be biased in some directions. A possible type of bias is related to the level of pre-existing knowledge about the effects of some measures: not all road safety measures have been equally well evaluated so far. An example: as knowledge about changes in road design is usually better available than knowledge on effects of changes in legislation, more instances will be found in the literature of evaluations of changes in road design. Therefore more measures related to road design will show up in the present CBA-analysis as compared to some other fields such as road safety education or legislation. More research efforts in the future can hopefully enable to yield a more complete list of measures for which CBA-estimates are known.

6.3. Multiple sources of uncertainty

By far the most important limitation of using cost-benefit analysis is its dependence on underlying assumptions. Assumptions related to three elements can play a decisive role:

- assumptions about the effectiveness of the measures
- assumptions about the costs of the measures
- assumptions about the size of the target group.

The **effectiveness** of a particular measure is rarely known precisely and often depends on the conditions in which the measure is implemented (e.g. whether roads are urban or rural, the thoroughness of the developed campaign…). However, meta-analyses on road safety measures are available in many cases and enable to use best estimates for effect sizes in typical conditions of application. For 22 out of the 29 measures, it was possible to use effect information based on meta-analyses. Moreover, meta-analyses also provide confidence intervals for the effect estimates that can be used for sensitivity analyses.

Even more uncertainty exists about both the **costs of the measures** and the **size of the target groups** as the latter are usually based on unique observations that might reflect some particular conditions in which the measure was taken and evaluated, but that are not necessarily generalizable. In order to execute meaningful CBAs, the three elements (costs of the measure, effects and target group) should apply to similar base conditions and thus match adequately. As an illustration of the practical difficulties to achieve this, consider the CBA on police enforcement of speeding. While Goldenbeld & Van Schagen (2005) provide an effectiveness estimate of of 21%, it was decided to utilize the more general estimate of the 18% of the meta-analysis of Erke et al. (2009) instead. The meta-analysis considers 45 studies across 7 measures therefore its results appear more robust for general-purpose use such as the current CBA. But Goldenbeld and van Schagen (2005) concerns the use of mobile radar checks on (sign posted) Dutch rural roads whereas the effect information from Erke (2009) concerns effects of all speed enforcement methods (fixed radar, surveillance, mobile radar, laser, patrolling) on all types of roads. So in this case the effect and cost information don't concern exactly the same measure. But still we think this is the best possible approach given the data limitations. In fact, this is where the approach of trying to find a generic CBA result reaches its limits.

We dealt formally with these forms of uncertainty by executing sensitivity analyses in order to show the effects of varying assumptions, even when rather extreme scenarios are defined. Following this logic, measures that remain cost-effective throughout all these scenarios are robustly cost-effective. Measures that never become cost-effective (e.g. automatic barriers on level crossings) turn out not to be suitable measures in general, at least as long as they are implemented under the average conditions that are reflected by the parameters used. As a rule of thumb the use of these measures should therefore not be encouraged for each and every possible location. However, this does not mean at all that they necessarily ought to be rejected. If the decision maker has reasons to believe that the applied parameters in specific circumstances are different from the ones used in the calculations in Table 3, the measure under scrutiny still can be a cost-effective measure. But at least such a position requires proper justification. The same reasoning applies to measures that relatively easily switch from not cost-effective ($BCR<1$) to cost-effective ($BCR\geq1$) throughout the various sensitivity analyses.

A general finding concerning the CBAs reported in this paper is that these CBAs are highly dependent on the assumptions made. It is important to realize that the dependency on these assumptions is not a weakness of the method but reflects weaknesses of the data that are usually available. An interesting observation was that in a number of the CBAs the most uncertain elements were the ones which one might have expected to be the easiest to collect: the measure costs and the target numbers of crashes. These are indeed the variables that are relatively straightforward to observe in the real world and therefore it should be relatively easy to collect data. Nevertheless the documented information on costs of measures and target crashes turned often out to be limited. It would be a good practice to report more extensively on costs of measures and on target numbers of crashes, both in scientific literature and in public policy documentation.

No formal sensitivity analyses were done based on **varying time horizons**. Although for most measures it is unlikely that changes in the applied time horizons within reasonable boundaries will deeply affect the outcomes of the cost-benefit analysis, the reader should keep in mind that time horizons are one of the input variables that eventually will determine the outcomes and therefore should be estimated with the best possible precision.

Unfortunately, no **side effects** were included in the CBA. The term side effects refers to effects other than traffic safety (e.g. mobility, environmental effects), which can be positive or negative. This choice was mainly the consequence of the apparent absence in the literature of reliable information on the nature and size of possible side effects for nearly all measures. While for many measures possible side effects are rather limited, they are likely to be more important for others, e.g. for those that potentially affect environmental quality or liveability, such as traffic calming or implementation of 30 km/h zones. As all welfare impacts should ideally be included as much as possible in CBA, there is a clear gap of knowledge here.

6.4. Comparibility with previous results

A number of cost-benefit estimates presented in this paper are reasonably comparable to earlier estimates in the literature (e.g. PROMISING, 2001), regarding specific measures such as the conversion of junctions into roundabouts or area-wide traffic calming. Furthermore, estimates that are in accordance with the ones provided herein have also been provided from past research, for instance for high risk sites treatment (ROSEBUD, 2006), for safety barrier installation (CEDR, 2008) or for channelization at junctions (Elvik et al., 2009). However, there have also been instances of differences in estimates, such as the measure of road lighting installation (PROMISING, 2001) or the measure of child restraints (Elvik et al., 2009).

These discrepancies can be explained by the same mechanisms as we described above and that basically refer to differences in input data (i.e. the variables Measurecost, Targetcrashes, Effectiveness and

Crashcost) that are used for each study. These differences are certainly related to differences in applicable conditions (e.g. differences in countries or road types) for each and every executed CBA. However they also reflect a clear lack of consistent knowledge.

6.5. Comparability of alternative options

CBAs are in the first place meaningful if they present the decision maker information on competing alternatives. In that case the alternative with the highest NPV should be chosen. However, in road safety, alternative policy options tend not to replace each other but rather to be in different areas of intervention. How to compare e.g. a road safety campaign with converting a number of intersections into a roundabout or making helmet wearing compulsory for bicyclists? Nevertheless, assuming that perfect information is available on all possible measures and their outcomes, still the set of measures with the highest NPV (after aggregation to a population level) should be taken.

7. CONCLUSIONS

The present paper shows the results of cost-benefit analyses of 29 road safety measures. Two outcome values are calculated for all the selected measures: the BCR and the NPV per unit of the measure. The measures were selected on the basis of their presumed effectiveness and were subsequently included based on the availability of input data (safety effects, costs of measures and the target number of cases).

According to our best estimates, 25 of these measures are cost-effective. Four measures (road lighting, automatic barriers installation, area wide traffic calming and mandatory eyesight tests) are not cost-effective in the best-estimate scenario. In total, 14 measures remain cost-effective throughout all scenarios, in the best case as well as in the worst-case scenario, whereas 10 other measures switch from cost-effective in the best case scenario to not cost-effective in the worst case scenario. Two measures (automatic barriers installation and area wide traffic calming) do not even become cost-effective in the best case.

Whenever using these results, one must be aware that CBA results are basically reflecting a combination of input data. These data are inherently uncertain and sometimes only valid for the specific circumstances in which the measures are usually established. This means that results are not necessarily generally valid or directly transferable to other settings. In general we can say that these generic CBA results are an interesting way to obtain proper ‘prima facie’ information, but in case someone wants to execute an a priori evaluation of some intended measures, these CBA should always be complemented with a project specific assessment of costs and benefits.

Finally, one can only observe that important knowledge gaps are present for many measures. Efforts in the scientific community should be encouraged to widely execute and disseminate results of efficiency analyses in road safety.

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