virtual

Open access
virtual testing protocols
for enhanced
road user safety

Cost-benefit analysis of innovative automotive safety systems

WP number: 6
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Cost-benefit analysis of innovative automotive safety systems

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Executive summary

Work Package 6 (WP6) of the VIRTUAL project has two main objectives. The first is to develop and describe a general tool for performing cost-benefit analysis (CBA) of safety systems. The second goal is to apply the tool to perform CBA of safety systems described and simulated in other Work Packages of the VIRTUAL project. The first objective was addressed by providing a CBA tool on the VIRTUAL Open Virtual Testing Platform (https://openvt.eu), based on a methodology incorporating novel elements. The second objective is addressed by applying the tool in two case studies: an active headrest aimed at preventing whiplash associated disorders (WADs) and autonomous emergency braking systems (AEBS) aimed at preventing car-pedestrian crashes and reducing injury severity.

The CBA methodology, which is embedded in the calculation tool, includes novel elements in the field of road safety. The methodology uses a detailed classification of injury types, through which any injury reductions are assessed and translated into quality of life gains, Quality Adjusted Life Years (QALYs) and monetary benefits. Moreover, a linkage with human body models (HBMs) is established to assess the safety benefits. Simulations of the impacts of a collision to the human body and the resulting injury probability changes, are used to estimate injury reductions. In addition, any impact on injury severity was assessed in a case study, whereas standard CBA usually only includes reduction in the number of injuries.

This report starts with an introduction to CBA in road safety. The elements of a CBA are explained and discussed, in particular with respect to application to vehicle safety, as well as data needs to assess a safety system in terms of monetary benefits and costs.

Guidelines are given to perform CBA on innovative safety systems. The guidelines were applied to develop the practical calculation tool for CBA of vehicle safety systems aimed at supporting stakeholders, such as the vehicle industry, road safety policy makers and non-governmental organisations (NGOs), to conduct CBAs and to support decision making. The VIRTUAL CBA tool uses standardised inputs but also asks for specific input parameters from users in order to compare the cost of implementing a safety system and its benefits in terms of monetary valuated avoided and reduced injuries. Collecting input parameters can be a challenge. Therefore, the report also provides sources and advice for data collection.

The VIRTUAL CBA tool was exemplarily applied in the two case studies, using output from virtual testing with VIRTUAL HBMs to assess safety systems. The cases illustrate the feasibility and added value of linking CBA to HBMs. Risk functions are required to translate simulation results to injury probabilities. However, due to lack of data availability, this kind of analysis cannot be performed for all injury types which can be analysed with the current CBA tool. Potential further developments of the CBA tool include the collection of specified input data such as disability weights, the option of allowing CBA for vehicle fleets instead of single vehicles, and the option of including crash risk based on vehicle km travelled. In future research, the methodology would be suitable for being applied to assess other vehicle safety systems, or for example, safety systems for public transport passengers.

List of abbreviations

ACC	Adaptive Cruise Control
ACEA	European Automobile Manufacturers Association
ADT	Activity Dependency Table
AEBS	Autonomous Emergency Braking System
ATD	Anthropomorphic Test Device
BCR	Benefit-Cost Ratio
CARE	Community Road Accident Database
CBA	Cost-Benefit Analysis
DALY	Disability Adjusted Life Years
ED	Emergency Department
FE	Finite Element
HBM	Human Body Model
HDR	Hospital Discharge Register
IPF	Iterative Proportional Fitting
MS	Microsoft
NCAP	New Car Assessment Programme
NDS	Naturalistic Driving Studies
NGO	Non-Governmental Organisation
NPV	Net Present Value
OVTO	Open Virtual Testing Organisation
SEK	Swedish Krona
STRADA	Swedish Traffic Accident Data Acquisition
QALY	Quality Adjusted Life Year
VIRTUAL	Open access virtual testing protocols for enhanced road user safety
VIVA+	Human Body Models developed in VIRTUAL
VT	Virtual Testing
VRU	Vulnerable Road User
VSL	Value of a Statistical Life
WAD	Whiplash Associated Disorder
WHO	World Health Organization
WP	Work Package
WTP	Willingness to Pay
YLD	Years Lived with Disability

1 Introduction

VIRTUAL is a Horizon 2020 project including the following main objectives:

- Provide open source Human Body Models (HBMs) for virtual safety testing. The models represent standing and sitting adult males and females;
- Make available test protocols for standardised use of virtual testing (VT) in different applications;
- Initiate the Open VT platform to openly provide the models and protocols (https://openvt.eu). By founding the Open Virtual Testing Organisation (OVTO), the maintenance of HBMs is also ensured after this research project;
- Demonstrate the power of HBMs and VT in the development of safety features to reduce fatalities and injuries by providing specific test cases. These cases show the power of VT and their ability to complement physical test regulations;
- Assess the cost-benefit ratio for safety systems and thus provide an economic basis for stakeholders emerging into the field.

The first four points were addressed in Work Packages (WP) 1-5 of the VIRTUAL project. Two HBMs were developed and are available to any user through the Open VT platform. The developed models are the VIVA+ 50F (50% percentile female) and 50M (50% percentile male) (John J. , et al., 2021); (John J. , Klug, Kranjec, Svenning, & Iraeus, 2022). Next to Anthropomorphic Test Devices (ATDs) – commonly known as crash-test dummies – HBMs are used supplementary to assess safety systems. HBMs are able to predict injury risks resulting from road crashes in more detail, i.e., with respect to injury type, body region and human characteristics, by simulating the impact of a crash to the human body. Once developed, virtual tests with HBMs can be run at low cost. HBMs not only allow testing for different ages, genders or sizes, they also allow simulating muscle activation and showing improved biofidelity because hardware limitations do not have to be considered. (Yang, 2018); (Linder & Svedberg, 2019).

This deliverable, D6.1, addresses the final objective on the list, assessing the costs and benefits of innovative safety systems in road traffic. In WP6, a methodology for conducting CBA of vehicle safety systems has been developed as well as a calculation tool in which the methodology is embedded. The tool is aimed at calculating the socio-economic costs and benefits of safety systems and provides insight in the costs of vehicle safety systems, the safety impacts (injuries and loss of quality of life) and the associated monetary benefits and the socio-economic return (balance of benefits and costs). The tool itself, including a description, input data, the licence and contact details of the developers to address questions or request support, are available on the Open VT platform (https://openvt.eu/cost-benefit-analysis/cost-benefit-tool).

In WP3 and WP4 of the VIRTUAL project, different use cases and safety systems have been addressed, aimed at enhancing safety for all occupants in cars as well as Vulnerable Road Users (VRUs). However, within the limited time and resources of the project, the required information was not available for all use cases. Only selected use cases have been considered for CBA in WP6 (printed bold in Table 1). This report includes examples of improved seat designs for reducing injury in rear-end crashes as well as active emergency braking to prevent cars from striking pedestrians and reduce impact speed, serving as demonstrator cases (marked with *). A complementary publication that will outline examples of active emergency braking to prevent cars from striking cyclists and to reduce impact speed, as well as design changes to tram fronts, to reduce injury to pedestrians has been planned. However, this report provides input parameters for all four use cases. The developed methodology and the CBA tool are in principle applicable to any vehicle safety system, provided that the required input data are available. These inputs include the type of injuries the safety system is targeted on, the crash risk (before and after the safety system has been implemented) and injury probabilities if a crash occurs (before and after safety system has been implemented).

Table 1 VIRTUAL use cases identified for CBA, weherby only those in bold were adressed within the project. Use cases marked with * are included in this report.

Aim	Targeted crash type	Safety system
Occupant protection	Rear-end crashes (motorised vehicles)	**Improved seat design for reducing injury in rear-end crashes (WP3) ***
		Design principles to protect against injuries in new seated postures and seating positions in cars (e.g. rearward facing) (WP3)
		Improved design of child restraint systems to enhance efficiency (WP3)
VRU protection	Car – Pedestrian	**Active emergency braking to prevent cars from striking pedestrians and reduce impact speed (WP4) ***
	Car – Cyclist	**Active emergency braking to prevent cars from striking cyclists and reduce impact speed (WP4)**
	Tram – Pedestrian	**Design changes to tram fronts to reduce injury to pedestrians (WP4)**

The tool serves to support road safety stakeholders in making decisions, i.e., with respect to developing, introducing and implementing (new) vehicle safety systems or concerning changes in regulations and legislation. The stakeholders include road safety policy makers, vehicle manufacturers, road safety non-governmental organisations (NGOs), vehicle assessment organisations and fleet owners. Since the tool requires in-depth knowledge on road safety, injuries and CBA, it is to be expected that some stakeholders require assistance from road safety researchers and consultants for practical applications of the tool.

This deliverable provides a comprehensive summary of the achievements of WP6 in the VIRTUAL project and includes descriptions of the VIRTUAL CBA tool and its methodology as well as application examples.

The chapters build upon each other but can be read independently as well. Readers who are familiar with CBA are recommended to skip Chapter 2. Some repetitive information is due to the stand-alone character of the chapters. The following topics are covered in this report:

- **Chapter 2: Guidelines for CBA:**
  General introduction to CBA and what is required to assess safety systems in road traffic.
- **Chapter 3: VIRTUAL CBA tool:**
  Detailed description of the tool. The CBA tool is based on the guidelines (Chapter 2).
- **Chapter 4: Input parameters and dedicated data sources:**
  Input parameters have been described and those relevant for VIRTUAL use cases are displayed.
- **Chapter 5: CBA use cases:**
  Examples of CBA on VIRTUAL safety systems based on virtual testing are given. In this chapter, the CBA tool (Chapter 3) is exemplarily used with input values from the database (Chapter 4).

- **Chapter 6: Discussion and Outlook**

In this document, we use "crash" instead of "accident" to be consistent with the CBA-tool and previous WP6 reports and publications. In this deliverable, "automotive" includes trams. Furthermore, we use "car" for "passenger car".

2 Guidelines for cost-benefit analysis (CBA)

This chapter presents guidelines for CBA and is dedicated to readers, who are not familiar with CBA. Other readers are recommended to start with Chapter 3 for a specific description of the VIRTUAL CBA tool. This chapter is to some extent based on a document prepared for the European Road Safety Observatory (ERSO) website in 2012 (Elvik, 2012) within the DaCoTa project funded by the European Commission.

The following questions are discussed in this chapter:

- What is cost-benefit analysis (CBA)?
- What types of data and information are needed to perform CBA?
- How can the benefits of innovative safety systems best be described and converted to monetary terms?
- How can the cost of innovative safety systems be identified?
- How can fixed parameters for analysis be determined?
- How can uncertainty in the results of analysis be assessed?

Initially, these topics are discussed in general terms. Then an example of a CBA is given in order to illustrate how such an analysis can be performed and the type of information that is required to perform a CBA.

2.1 What is a cost-benefit analysis?

CBA is a formal analysis of the impacts of a measure or programme, designed to assess whether the advantages (benefits) of the measure or programme are greater than its disadvantages (costs). Within VIRTUAL, the relevant measures are innovative safety systems designed to reduce the number of crashes and/or the severity of injuries. CBA is based on welfare economics. There are numerous textbooks explaining in detail the problems encountered in a CBA and how to solve these problems (Boardman, Greenberg, Vining, & Weimer, 2011); (Pearce, Atkinson, & Mourato, 2006); (Hanley & Spash, 1993); (Layard & Glaister, 1994); (Mishan, 1988); (Alder & Posner, 2001); (Sen, 2000). Therefore, only the main features of CBA are described here. The main steps of CBA, as applied in VIRTUAL, are as follows:

1. Develop and define measures or programmes to be subjected to analysis. In VIRTUAL, the following innovative safety systems, which are elaborated on below, were addressed and prepared for conducting CBA:
   - Improved seat designs for reducing injury in rear-end crashes
   - Active emergency braking to prevent cars from striking pedestrians and reduce impact speed
   - Active emergency braking to prevent cars from striking cyclists and reduce impact speed
   - Design changes to tram fronts to reduce injury to pedestrians
2. Estimate in numerical terms the expected impacts of each safety system on the number of injuries and injury severity.
3. Convert impacts to a generic scale for health, e.g., Quality Adjusted Life Years (QALYs) or Disability Adjusted Life Years (DALYs). These are independent, continuous scales permitting a

precise description of changes in health state. A QALY value of 1 for a year represents a perfect health state and the value of 0, death. States of reduced health are assigned values between 0 and 1, the closer to 0, the worse the health state. A DALY also include values between 0 and 1, however the scale is in the opposite direction of QALYs. Thus, 0 is no loss of health and 1 is complete loss of health, i.e., death. A DALY of 0.2 corresponds to a QALY of 0.8. Both QALYs and DALYs refer to a period of one year.

4. Convert impacts on health to monetary terms.
5. Obtain estimates of the costs of each safety system.
6. Determine fixed parameters (explained in the following) for analysis.
7. Compare benefits and costs for each innovative safety system involved in the measure/programme under analysis.
8. Conduct a sensitivity analysis or a formal assessment of the uncertainty of estimated benefits and costs for each safety system.

Regarding the first point, it is essential that each innovative safety system is described in sufficient detail to support a numerical estimate of its impacts. Using improved seat designs to reduce injury in rear-end crashes, as an example, means that it is necessary to know (or at least estimate):

- The expected number of rear-end crashes a car will be involved in as the struck vehicle during its lifetime.
- The expected distribution of injuries by severity in these rear-end crashes.
- The impact of better seat design on the frequency and severity of injuries in rear-end crashes. Impacts should preferably be specified according to injury severity, at least on a crude scale, but ideally as a function of a continuous measure of severity.
- The additional cost of improved seat design, compared to standard design, and what the cost of repairing or replacing a seat that has been involved in a rear-end crash, is.

If this information is available, it provides the data needed for Steps **1, 2, (3)** and **5** of a CBA.

Step **4** converting safety benefits to monetary terms is discussed in a subsequent section of this chapter. The determination of costs is also discussed more in detail in subsequent sections of the deliverable.

The information entered into and utilised in a CBA is of two types: variable parameters and fixed parameters. The variable parameters are all items that are unique to each analysis and vary from case to case. The fixed parameters are the same in all analyses and defined in Step **6,** which are further explained in Section 2.5.

In Step **7**, the data for benefits and costs of the safety systems are compared. The results of any CBA are uncertain. Sources of uncertainty and how to assess them are discussed in greater detail later in this chapter (Step **8**).

2.2 Types of data and information needed in a CBA

In most CBAs, multiple impacts of the evaluated measure are relevant and extensive data are required. CBA is widely applied in road investment planning. In CBA of road investments, relevant impacts include not only road safety, but also travel time, vehicle operating costs, local environmental impacts, global warming and possibly wider impacts on land use and economic development. The analyses in VIRTUAL are simpler in the sense that the principal impact is changed by the number and severity of injuries. Nevertheless, despite this simplification, the data required to perform a CBA in the

VIRTUAL project must be quite detailed. The main types of data required for conducting a CBA in VIRTUAL include:

- The expected number of target injuries specified according to injury severity per unit of time per unit of implementation (see further details below).
- The estimated effect of an innovative safety system on target injuries, specified according to injury severity.
- An estimate of the duration of the impacts of an innovative safety system (normally identical to the lifetime of a vehicle).
- A monetary valuation of changes in the number and/or severity of injuries resulting from the innovative safety system.
- An estimate of the cost, ideally the production cost, of one unit of an innovative safety system.

Target injuries are those injuries that are influenced by an innovative safety system. As an example, target injuries for an innovative safety system, targetting standing public transport passengers, would be the expected number of injuries sustained by passengers falling inside the vehicle per year per vehicle. It is necessary to know or be able to estimate the expected number of injuries at this early level of analysis, since any biomechanical models or analyses will apply to a single vehicle, see, for example Palacio et al. (Palacio, Tamburro, O'Neill, & Simms, 2009). Moreover, cost estimates for innovative safety systems will usually also refer to a single vehicle. It is convenient to refer to the number of events during a period of one year.

For example, based on a review of studies of injuries to public transport passengers (Elvik, 2019), it is estimated that the risk of injury is about 0.30-0.50 per million passenger kilometres. If a public transport vehicle produces 1 million person-kilometres per year (equivalent to each vehicle driving 50,000 kilometres per year with an average of 20 passengers on board), the expected annual number of events per vehicle is 0.30-0.50.

The objective of safety systems is to reduce the number and/or severity of target injuries. To perform a CBA, it is necessary to quantify the expected impact on target injuries. Ideally, the changed injury risk should be specifically available in terms of its type and severity. For example, the risk of Abbreviated Injury Scale (AIS)2 rib fracture, described below, was reduced by introduction of the safety system from 15% to 10%, per vehicle per crash. Using the VIVA+ models, the risk for specific injuries can be predicted from simulations in which the safety system is integrated. The effect of an innovative safety system can then be estimated in terms of the change in the probability of a specific injury. The overall effect is obtained by comparing the probabilities with and without the safety system and can then be converted to an expected change in the number of events per vehicle per year.

Example
The risk of injury per million passenger kilometres is 0.30. A safety system has a potential to reduce the risk, for example, to 0.20. For a vehicle producing 1 million passenger kilometres per year, this corresponds to a reduction of the expected number of events by 0.1. Ideally, the 0.10 injuries prevented (or 1 injury in 10 years) should be specified according to type of injury and injury severity. This will permit a more precise CBA, as the cost of injury vary substantially according to severity.

It is reasonable to assume that new safety systems will be installed in new vehicles before they reach the market. The effect of the systems will then last for the service life of the vehicle. However, some systems may need to be replaced or repaired if they have been deployed in a crash. Thus, seats designed to reduce Whiplash Associated Disorders (WADs) in rear-end crashes would normally have to be replaced or repaired if the protective mechanism has been activated in a crash. An assumption must then be made about when during the service life of a vehicle, a crash in which the safety system is deployed, is likely to occur.

Biomechanical studies may produce output in various scales that must be translated to a common scale for conversion to QALYs (see Section 2.1). An example is given below:

- AIS
- MAIS
- ISS
- ICD → EUROCOST classification → QALY
- RPMI
- FCI

AIS is the Abbreviated Injury Scale (Civil & Schwab, 1988). The injury severity is coded between 1 (minor) and 6 (Maximal – currently untreatable). These first six digits of the AIS code specify the injury by body region. A person with injuries to more than one body region will be assigned one AIS code for each injury. AIS codes can be converted to main diagnoses according to the International Classification of Diseases (ICD) (Clark, Black, Skavdahl, & Hallagan, 2018), which in turn can be converted to EUROCOST values (more on EUROCOST below). ICD is a very detailed classification system and widely used in hospitals. In a study of injuries to cyclists in the city of Oslo, 255 different diagnoses were assigned to 2,184 injured cyclists (Elvik & Sundfør, 2017). These were grouped into 30 diagnoses and mapped onto the EUROCOST system of disability weights assigned to 39 different injury diagnoses. The disability weights were converted to DALYs and had monetary values assigned to them. For an updated description of AIS, see Genarelli and Wodzin (Gennarelli & Wodzin, 2005).

MAIS is the maximum AIS severity. Thus, if a person has an AIS1 head injury and an AIS 3 leg injury, the MAIS is 3.

ISS is the Injury Severity Score that provides an overall score for patients with multiple injuries. It is based on AIS and equals the sum of the squared values of the three highest AIS-scores. Thus, if three injuries have AIS values of 2, 3 and 4, ISS equals 29 (4 + 9 + 16). The ISS score ranges from 0 to 75.

RPMI is Risk of Permanent Medical Impairment. RPMI can be computed for injuries with known AIS-scores based on a study by Malm et al. (Malm, Krafft, Kullgren, Ydenius, & Tingvall, 2008). Probability estimates have been developed for three levels of permanent impairment: 1%, 5% and 10%. These levels of impairment correspond, as an approximation, to QALY values of 0.99, 0.95 and 0.90. Note, however, that since impairment is permanent, the age and remaining life expectancy of the victim must be taken into account, and QALY values added for all remaining years of life expectancy (with or without discounting future years of life).

FCI is the Functional Capacity Index. This FCI was developed in the United States by MacKenzie et al. (MacKenzie, Damiano, Miller, & Luchter, 1996). It has been applied to estimate the cost of traffic injury in the United States. Scales with up to seven levels of functioning are applied to ten bodily functions. This permits a quite detailed description of overall health state. Furthermore, AIS codes can be translated into FCI.

The most detailed system developed to date for assessing health loss associated with injuries is the EUROCOST system (Haagsma, et al., 2012). In contrast to the above-mentioned scales, the EUROCOST system is different. This system assigns disability weights to more than 30 injury diagnoses, based on expert judgements provided by a group appointed by the World Health Organization (WHO). The disability weights assigned to specific injuries according to the EUROCOST system are shown in Table 2. The EUROCOST system was developed in Europe, however, it is applicable outside of Europe as well.

The first columns show disability weights for the acute phase of injury. Emergency Department (ED) refers to those treated as outpatients. Hospital Discharge Registers (HDRs) refer to those admitted to hospital. The proportion involving lifelong consequences has been identified, for each group. Finally, the disability weight for lifelong consequences is given in the rightmost column. The disability weights apply to a period of one year. Victims of permanent impairment are thus assumed to remain in the same condition indefinitely. The disability weights are applied as indicators of quality of life in CBA and are thus interpreted as utility measures. It should also be noted that disability weights have not been developed for all injuries listed in Table 2 and that the table is not complete. Thus, some serious permanent injuries like amputation and blindness are not included. Disability weights for amputation and blindness were developed in the global burden of disease study (World Health Organization (WHO), 2004). To apply the disability weights developed by the WHO, the HBMs developed in VIRTUAL have been designed to predict at least some of the injuries listed in Table 1 and the likelihood of an injury being lifelong.

Table 2 Disability weights assigned to injuries. Taken from Haagsma et al. (2012)

Injury group	**DW acute phase**		**Proportion lifelong consequences (%)**		**DW lifelong consequence**
	ED	**HDR**	**ED**	**HDR**	
Concussion	0.015	0.1	4%	21%	0.151
Other skull–brain injury	0.09	0.241	13%	23%	0.323
Open wound on head	0.013	0.209	–	–	–
Eye injury	0.002	0.256	0%	0%	–
Fracture of facial bone(s)	0.018	0.072	–	–	–
Open wound on face	0.013	0.21	–	–	–
Fracture/dislocation/sprain/strain of vertebrae/spine	0.133	0.258	–	0%	–
Whiplash injury/sprain of cervical spine	0.073	ND	ND	ND	ND
Spinal-cord injury	ND	0.676	ND	100%	ND
Internal-organ injury	0.103	0.103	–	–	–
Fracture of rib/sternum	0.075	0.225	–	–	–
Fracture of clavicula/scapula	0.066	0.222	2%	9%	0.121
Fracture of upper arm	0.115	0.23	17%	10%	0.147
Fracture of elbow/forearm	0.031	0.145	0%	8%	0.074
Fracture of wrist	0.069	0.143	0%	18%	0.215
Fracture of hand/fingers	0.016	0.067	0%	0%	0.022
Dislocation/sprain/strain of shoulder/elbow	0.084	0.169	0%	18%	0.136
Dislocation/sprain/strain of wrist/hand/fingers	0.027	0.029	0%	0%	–
Injury to nerves of upper extremity	ND	ND	ND	0%	–
Complex soft-tissue injury of upper extremity	0.081	0.19	3%	15%	0.166
Fracture of pelvis	0.168	0.247	30%	29%	0.182
Fracture of hip	0.136	0.423	14%	52%	0.172
Fracture of femur shaft	0.129	0.28	46%	35%	0.169
Fracture of knee/lower leg	0.049	0.289	23%	34%	0.275
Fracture of ankle	0.096	0.203	12%	35%	0.248
Fracture of foot/toes	0.014	0.174	8%	39%	0.259
Dislocation/sprain/strain of knee	0.109	0.159	8%	0%	0.103
Dislocation/sprain/strain of ankle/foot	0.026	0.151	4%	26%	0.125
Dislocation/sprain/strain of hip	0.072	0.309	23%	30%	0.128
Injury to nerves of lower extremity	ND	ND	0%	0%	–
Complex soft-tissue injury of lower extremity	0.093	0.15	10%	13%	0.08
Superficial injury (including contusions)	0.006	0.15	–	–	–
Open wound	0.013	0.093	–	–	–
Mild burn(s)c	0.055	0.191	0%	0%	–
Poisoning	0.245	0.245	0%	0%	–
Multitrauma	ND	ND	ND	ND	ND
Foreign body	0.044	0.06	–	–	–
No injury after examination	–	–	–	–	–
Other and unspecified injury	0.111	0.212	–	–	–

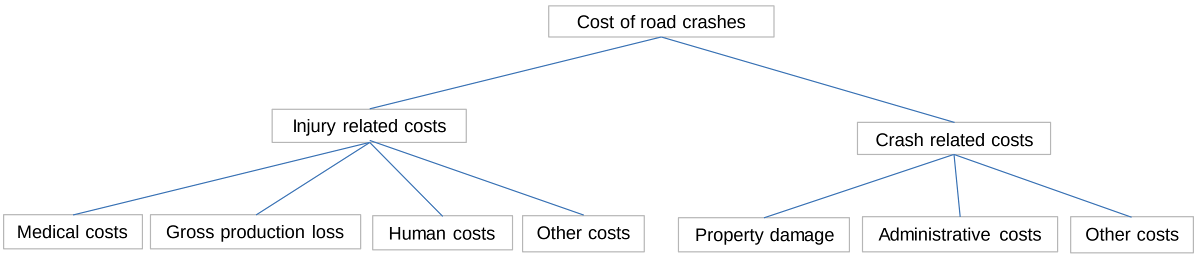
ND = not determined

Monetary valuation of impacts and cost estimates for safety systems are discussed below.

2.3 Monetary valuation of prevented injuries

Road safety improvements can be expressed in terms of money using estimates of the socio-economic cost resulting from road crashes. There are six main components of the socio-economic cost of road crashes. These are shown in Figure 1.

Figure 1 Main components of costs related to injuries and crashes. Based on Wijnen et al. (2017)



The six components include:

- Medical costs, such as cost of transportation to the hospital and cost related to hospital and non-hospital treatment.
- Loss of production due to the inability to work due to road casualties.
- Human cost: the intangible cost of loss of quality of life and life years.
- Cost related to property damage, such as damage to vehicles and infrastructure.
- Administrative costs, including cost related to police fire department, insurance and legal issues.
- Other costs, such as funeral, congestion and cost of vehicle unavailability

The various components of a valuation differ in terms of how they are manifested in economic transactions. The direct costs, such as medical cost, property damage and administrative costs, are real expenditures. In principle, these costs can be retrieved or at least roughly identified in the accounts of hospitals, insurance companies, the police, courts, car repair shops and households. The method for estimating such costs is known as the ‘restitution costs’ method, which is aimed at measuring the cost of resources required to restore road traffic victims and their relatives and friends, to a similar state to had they not been involved in a road crash (Wijnen, et al., 2017); (Alfaro, Chapuis, & Fabre, 1994). The expenditure for restoring, such as expenditure for medical treatment or vehicle repair, has been assumed to reflect the monetary valuation of these resources.[1]

Estimates of lost productive capacity partly reflect monetary transactions; these costs are partly of a more abstract nature. In particular, lost productive capacity attributable to a fatality is usually estimated as the present value of future earnings, referred to as the human capital approach (Wijnen, et al., 2017); (Freeman, Herriges, & Kling, 2014); (Alfaro, Chapuis, & Fabre, 1994). Human capital represents the value of what an individual could have produced if remaining alive; this is uncertain

[1] Note that, according to the economic welfare theory underpinning cost-benefit analysis (see e.g. Boardman et al., 2011), the monetary transaction in itself is not regarded a socio-economic costs. The transfer of money from stakeholder A to stakeholder B is a cost for A but a benefit for B, so on the societal level there is no net benefit. The welfare impact is the value of resources required for medical treatment, vehicle repair, etc. The impact is monetised using market prices for these activities. For further explanation, see e.g., Wijnen et al. (2017).

and therefore most appropriately interpreted as a loss of productive potential or capacity, not an actual loss of production.

The willingness to pay (WTP) approach is generally recommended for monetising human cost (Wijnen, et al., 2017); (Freeman, Herriges, & Kling, 2014); (Elvik, 2012); (Alfaro, Chapuis, & Fabre, 1994). Willingness to pay for a reduced number of road accidents reflects the hypothetical demand for improved safety. It does not reflect any actual monetary transactions. The WTP for reducing statistical risks by an amount that corresponds to the prevention of one death (often referred to as the value of a statistical life) is completely unrelated to, for example, post cost generated by the death of an individual in the personal environment, for example. The latter costs are at least two orders of magnitude smaller than the valuation of preventing a death. In countries that apply the WTP approach for valuing road safety, this component normally represents more than half, in some cases nearly the whole, monetary value assigned to improving road safety (Wijnen, et al., 2017). The valuation of improved road safety in terms of WTP is not subject to market transactions. Hence, although representing real benefits of improving road safety, i.e., real welfare gains, this approach will not be realised in terms of added income or profit.
Recent experience, in particular after the European New Car Assessment Programme (EuroNCAP) was launched, shows that safety sells. Car manufacturers may at least to some degree, therefore, be able to convert improved safety into higher earnings or profit. Nevertheless, one should not forget the possibility that a safety system whose societal benefits exceed the costs, may not provide business benefits to car manufacturers exceeding the cost of the system.

In the SafetyCube project, a survey of official monetary valuations of road safety in more than 30 European countries was conducted (Wijnen, et al., 2017). The data were carefully quality checked and converted to 2015 values in Euros applying country-specific price indexing and currency conversion by means of purchasing power parities. These valuations are the most updated and detailed available for Europe and we propose to use them in VIRTUAL. The monetary valuation of road safety was found to vary considerably between countries. Some of the variations may be explained by income differences, but the most significant difference was attributable to differences in the methods used to estimate the valuations. In general, valuations were higher in countries applying the willingness-to-pay approach than in countries not doing so. Harmonised cost estimates were developed based on guidelines for road crash costs and current best practices. In particular, the COST313 guidelines developed by the European Commission nearly 25 years ago (Alfaro, Chapuis and Fabre 1994), and still regarded valid, were used as well as a recent review of road crash cost studies (Wijnen & Stipdonk, 2016).To develop harmonised cost estimates, firstly standard (average) European cost estimates were made using cost estimates from countries applying methods consistent with international guidelines and best practices. The above mentioned standard valuations are shown in Table 3. Next, harmonised cost estimates for each individual country were developed using value transfer. This means that national cost estimates were complemented by including components excluded by some countries, using the standard cost estimates. Also, national cost estimates were replaced by the standard cost estimates if not consistent with the guidelines.

Table 3 Harmonised costs of traffic injury in Europe, based on Wijnen et al. 2017. Amounts in Euros

	Medical costs	Production loss	Human costs	Property damage	Administra-tive costs	Other costs	Total (unit) costs
Fatalities	5,430	655,376	1,587,001	11,555	6,346	3,638	2,269,346
Serious injuries	16,719	43,627	230,385	7,622	4,364	413	303,130
Slight injuries	1,439	2,669	15,597	5,317	1,876	519	27,418
Fatal crashes	11,757	727,616	1,809,467	17,542	8,891	3,817	2,579,089
Serious injury crashes	19,158	50,285	263,945	11,143	5,557	709	350,796
Slight injury crashes	1,957	3,629	21,212	7,231	2,677	634	37,340
PDO crashes	0	0	0	2,795	764	400	3,960

The three upper rows refer to injuries and the four lower rows refer to crashes. The values are applicable in CBA at the European level, when one does not wish to specify a particular country the results apply to. Note, however, that the values for serious and slight injuries are, ultimately, based on national definitions of these injury severities. It is only the cost components and each method of estimation that has been harmonised. While an internationally standardised definition of serious injuries has been adopted (MAIS 3+), it is yet to be implemented in all countries. For slight injuries, there is no standard European definition.

When performing CBA of safety systems affecting injury severity, a monetary value must be assigned to the health consequences resulting from any injuries. QALYs or DALYs can be used as a measurement unit for health consequences, in addition to impact on medical costs and productivity. These concepts combine impact on mortality (fatalities) and morbidity (injuries). Concerning injuries, QALYs and DALY include Years Lived with Disability (YLD), which combine the duration of the health consequences of injuries and the severity. Disability weights, in the case of DALYs ranging from 0 (perfect health) to 1 (death), are used to express severity.

Quality of life gains can be monetised using a value per QALY. Monetary valuations of QALY can be derived either from a stated preference study, in which people are asked about the amount of money they are willing to pay for a specific health improvement (e.g. (Gyrd-Hansen, 2003); (Nimdet, Chaiyakunapruk, Vichansavakul, & Ngorsuraches, 2015)). Based on a literature review, Wijnen (2021) gives an overview of monetary values of a QALY which are relevant for road safety applications (Wijnen W. , 2021). The range for values found in the 18 selected studies is extremely broad: €1,355 to €386,173 per QALY (2019 price level). The median values were €16,259 for all studies and €20,125 for European studies.

The current values of road injuries are higher than the values that would result from applying monetary values of a QALY/DALY from WTP studies (Schoeters, et al., 2017). This difference is likely to be, at least partly, explained by differences in methodologies. Different methods are used for eliciting QALY preferences (disability weights) than for eliciting monetary values in WTP studies. Furthermore, QALY/DALY values are based on one specific type of WTP method (contingent valuation), while different types of WTP-methods are used for the valuation of fatal risk (Schoeters, et al., 2017).

Another approach is to derive the value of a QALY from the value of a statistical life (VSL) or from the value of a statistical injury. A fatality corresponds to the loss of a certain number of years of living.

Thus, for Norway, the mean remaining life expectancy of traffic fatalities is about 42.3 years. The value of preventing a traffic fatality can then be converted to the value of a gained life-year. As an example, if the harmonised value of preventing a fatality given in Table 3 is used, a remaining life expectancy of 40 years is assumed, and future years of life discounted at an annual rate of 4%, the value of a life-year becomes approximately €115,000.

Deriving QALY values from the VSL yields high value, which is more than five times higher than values from preference studies (Ryen & Svensson, 2015). The SafetyCube project (Wijnen, et al., 2017) determined a standard value of human cost for serious injury at €250,000 (2020 prices). A Dutch study shows that the number of QALYs lost due to a serious injury is estimated at 2.1 QALYs (Weijermars, et al., 2018), which results in a value per QALY of about €120,000.

Based on this literature, a plausible range of the value per QALY is €20,000 - €120.000 with the default value at a rate of approximately €70,000.

When the value of a gained life-year is known, it can be used as a reference to value changes in health state, measured in terms of QALYs or DALYs. As an example, a WAD has a disability weight of 0.073 according to the EUROCOST system for assessing the disability caused by various injuries (Haagsma, et al., 2012). The value of preventing a WAD becomes 0.073 · 70,000 = €5,110.

Further assessment of monetary valuation of QALYs and DALYs was made in VIRTUAL. We encountered the fact that literature mainly concentrates on the VSL and pays little attention to non-fatal road injuries. This is problematic, because the socio-economic costs of non-fatal road injuries are often (much) higher than the cost of fatalities, and they have gained more attention in road safety policy making in recent years. Therefore, we dedicated resources to review and summarise the best options for non-fatal road injuries. A manuscript outlining the results has been submitted.

2.4 The cost of intervention

The cost of a road safety measure is the value, in monetary terms, of the resources used to produce the measure. This applies to innovative safety systems and all other road safety measures. These resources may include workforce, machinery, land and natural resources. The cost of producing an innovative safety system will be referred to as a direct cost. Direct costs are, for example, the cost of converting a junction to a roundabout or the cost of installing electronic stability control in a car.

Both roundabouts and electronic stability control must be developed and planned before they are implemented. The cost of technological innovation, development and planning precede the cost of implementing a new safety system. However, estimating these costs is difficult as they may be part of general innovation and decision making processes. For that reason, separate estimates are normally not included when the cost of a road safety measure is estimated.

While designing a roundabout is a routine activity, technological innovations resulting in new vehicle safety features may involve many years of research performed by large teams of highly qualified scientists. The cost of the research involved in developing innovative safety systems will obviously be considerably greater than the production cost of the systems, which may be in the order of hundred Euros per car. Also, estimating these costs is difficult as they may be part of general innovation and decision making processes.

One reasonable alternative would be to rely on market prices, due to vehicle manufacturers aiming to make a profit when selling their end product and will, hence, pass on all costs of technological development to consumers. The cost of developing the system, incurred by the manufacturer before the system is ready for the market, will be incorporated into the market price of a vehicle being equipped with the system.

The cost of the innovative safety systems that were and continue to be studied in VIRTUAL are, however, not very well known. More information on costs can be found in Section 4.2 and in Chapter 5.

Thus, as an example, a seat providing better protection against WAD may not necessarily be more expensive to manufacture than a standard seat. However, this does not mean that it would be correct to assign a cost of zero in a CBA. To develop the new seat, research and testing would be required. These costs, incurred before the seat is marketed, must be incorporated into the market price of the seat, although the technical manufacturing of the seat may not cost more than a standard seat. The development costs, when portioned out per seat, will of course be lower per seat the larger the number of seats manufactured. Thus, obtaining realistic estimates of the cost of innovative safety systems is by no means a simple task. The following costs must be estimated in order to be able to perform a CBA:

- Cost of developing innovative safety systems.
- Additional costs of manufacturing innovative safety systems.
- Cost of repairing or replacing safety systems that have been deployed in crashes.

The first item is the most difficult to estimate, since it should, as indicated above, be allocated to each vehicle and reflect the price manufacturers will charge to retrieve any development costs. An example of a CBA given in Section 2.8 shows how costs can be estimated.

2.5 Fixed parameters in the CBA

As mentioned above, any CBA consists of a mixture of variable input and fixed parameters. The variable input is unique to each analysis. The fixed parameters are the same in every analysis. Fixed parameters in CBA include:

- The monetary valuation of relevant impacts.
- The time horizon for impacts.
- The discount rate.

In some applications, fixed parameters like the opportunity cost of public funds raised by general taxation are relevant. In VIRTUAL, however, it is assumed that the private sector, in particular car owners or owners and operators of buses or other public transport vehicles, will pay the cost of the safety systems. Hence, the issue of how taxation influences choices does not arise.

Recommendations on values used as fixed values, which have also been used within VIRTUAL, are provided in Chapter 2.9. With respect to monetary valuation, we propose using the estimates developed in SafetyCube. These estimates have already been implemented in a web-based tool for efficiency analysis. They are based on official valuations in 31 European countries and are thus endorsed by the governments in these countries. The values can easily be updated by means of price indexes.

There is a choice between using the values for each country and the harmonised average values for Europe, which include all relevant cost components which are methodologically consistent with international guidelines and best practices (unlike the cost estimates for each country, which do not always include all cost components or use other valuation methods). Since the market for motor vehicles and road safety systems is essentially global, we propose using the harmonised valuations. Performing a CBA that only applies to a single country would not be useful.

Automotive safety systems will either last as long as the vehicle lasts, or until their deployment in a crash necessitate repair or replacement. For cars, the scrapping age varies between countries, typically when a car is between 15 to 20 years old. Adopting a time horizon for impacts of 15 years is reasonable. For public service vehicles, in particular buses, a somewhat shorter service life of 10 years may be realistic. Trams, on the other hand, are often in service for 30 years or more before scrapping.

In the SafetyCube project, data were also collected on the discount rate countries use in CBA. Unfortunately, answers were incomplete. The European Commission has guidelines for the applicable discount rate to be used in CBA: 3% for non-Cohesion countries and 5% for Cohesion countries (European Commission, 2014). The discount rates recommended by the European Commission have been adopted in VIRTUAL.

A short explanation about the concept of a discount rate is given below. The discount rate is used in order to make costs and benefits occurring at different points in time comparable. Discounting enjoys almost unanimous support among economists despite being controversial outside the ranks of economists (see, e.g. (Hauer, 2011)). Different reasons have been given for discounting. One established argument is that money invested or put in a savings account earn interest. Thus, if we need €100 ten years from now, we do not need to deposit €100 in our bank account. A smaller amount, say €90, will be sufficient, as it will grow to €100 during the ten years. Hence, the present value of €100 paid ten years from now is €90.

Another argument for discounting is time preference: we generally prefer to receive the benefit now to getting the same benefit in the future. To prefer receiving the benefits now rather than later is referred to as positive time preference. There is no doubt about the fact that most people have a positive time preference. For example, most people would prefer to book a holiday now rather than 6 months later, because they might not be certain if they will be able to go on holiday then. With respect to vehicle safety, people are likely to prefer installing a safety device now rather than next year. In this case, the benefits of the safety device might be lower in the future because of a long-term trend of declining crash risk.

In general, the present value of a benefit (or cost) is estimated as:

Present value = $\sum_{i=0}^{n} \frac{B_i}{(1+r)^i}$

In this formula, B denotes the benefit in year i and r is the discount rate. The summation is from year 0 to year n, the end of the time horizon considered. Thus, if the benefit in year 0 is 100, in year 3 it will be (with an annual discount rate of 3%):

$100/(1.03)^3 = 100/1.093 = 91.5$

As the years pass, the present value of a constant stream of benefits reduces over time.

2.6 Comparing benefits and costs

There are two main ways to express the efficiency of road safety measures based on CBA:

- Net present value (NPV): the present value of the benefits minus the present value of the costs.
- Benefit-cost ratio (BCR): the present value of the benefits divided by the present value of the costs.

Some textbooks on CBA discuss other decision criteria, such as the internal rate of return, which is the discount rate that would equalise the present value of benefits and costs (NPV is zero). However, in road safety applications, only NPV and BCR are commonly used (see e.g. (Martensen, et al., 2018)).

In most cases, NPV and BCR result in different ranking of interventions, due to the different sizes of the projects under consideration. Large projects, e.g. affecting a large group of road users, are likely to be more costly but also to yield larger safety benefits. Consequently, the NPV is likely to be greater than for smaller sized projects, even if the BCR of these latter projects is higher.

NPV is often preferred above BCR as a decision rule in CBA (see e.g. (Boardman, Greenberg, Vining, & Weimer, 2011)). One of the arguments is that the BCR can be manipulated if negative impacts, such as negative travel time impacts, are (erroneously) treated as costs instead of negative benefits (i.e. in the denominator instead of the numerator of the BCR). This argument does not apply to the safety systems considered in VIRTUAL because we did not take any other benefits than (positive) safety impacts into account.

Another argument in favour of NPV is that a higher NPV represents a greater welfare increase, which is, from a socio-economic perspective, the ultimate aim of interventions. Projects with a high BCR may have a limited impact on welfare if the benefits and costs are relatively low. If a choice had to be made between projects of different size, regardless of budget limitations, indeed NPV is preferred as it shows which project has the highest net benefits. If there is a fixed budget available for interventions, such as implementing (road safety) measures, implementing the one with the highest BCR and then proceeding to implement the second highest, etc., until the budget is spent will ensure the best value for money for the budget under consideration.

For the VIRTUAL CBA, we calculate both the NPV and BCR.

2.7 Assessing uncertainty in CBA results

The results of any CBA are uncertain. There are many sources of uncertainty (Elvik, 2010):

- The definition and estimation of target injuries influenced by a safety system.
- The distribution of target injuries by severity.
- The translation of biomechanical estimators, such as maximum acceleration or strains to an expected number or probability of injuries.
- The effect of innovative safety systems on the number and severity of injuries.
- The monetary valuation of safety benefits.
- The cost of innovate safety systems.

VIRTUAL has attempted to address all these sources of uncertainty.

It may be possible to quantify uncertainty in the definition and estimation of target injuries. Consider, for example, non-collision injuries to passengers on public transport. In most studies, two main groups of injury are specified: (1) falls on board, and (2) falls when boarding and alighting. Both categories normally refer to standing passengers or passengers who are moving around in the door area to enter or leave a vehicle. It is not obvious that these categories include all non-collision injuries. Even seated passengers can fall and be injured if a vehicle brakes hard or makes a sharp turn. A seated passenger can be thrown out of the seat onto the floor of the vehicle, or may strike against bars, seatbacks or other objects inside the vehicle. Most studies do not define very accurately which injuries are deemed non-collision injuries. However, even if all systematic errors could be explained and excluded, the expected number of injuries according to a limited sample will be statistically uncertain, equal to the random variation around the expected number. This variation can be estimated by assuming a Poisson distribution. As an example, if the expected annual number of falls in a public transport vehicle is 9, the standard error is the square root of the expected value, or 3. This means, it is most likely that 6 to 12 falls occur in one year.

The distribution of non-collision injuries to public transport passengers by severity may also differ between studies. Thus, in the studies reviewed by Kendrick et al. (Kendrick, Drummond, Logan, Barnes, & Worthington, 2015), one study stated that 15% of injuries were AIS3 or 4, another study stated that 14% of injury victims were admitted to hospital and a third study stated that the share of killed or seriously injured passengers in non-collision events was 8.1% when boarding, 11.5% when alighting, 7.2% when standing and 4.1% when sitting. Neither the level of detail nor the scales used for injury severity were the same in all studies. One study used AIS, another admission to hospital and a third the injury severity categories in official accident statistics to indicate injury severity. One study specified four types of events, the other two apparently treated all non-collision events as a single group. This lack of consistency generates uncertainty about what assumptions one should make in CBA of non-collision events in public transport with respect to the distribution of injuries by severity. Still, between them, the studies at least indicate a plausible range for the share of injuries that are severe (with 4% the lowest and 15% the highest of the percentages quoted above).

With respect to the monetary valuation of safety benefits, there is uncertainty with respect to the monetary valuation of a QALY, as noted in Section 2.3. We represented this uncertainty by means of a best estimate, a lower estimate and an upper estimate.

We envisaged that it is not easy to meaningfully quantify the uncertainty of the cost of new safety systems. To some extent, these costs needed to be stipulated and reflect judgement more than data. Hence, there is no meaningful statistical estimators of uncertainty, such as standard deviation. There is, nevertheless, uncertainty about costs per vehicle as a result of economies of scale and learning effects. If vehicles are produced in large series, it is likely that economies of scale will reduce the cost of production per vehicle. To estimate costs, assumptions must therefore be made about the number of units that are expected to be produced. On top of economies of scale, there may be a learning effect. When a new element is produced for the first time, routines may not have settled into their most effective form yet. Repetition usually makes for faster and less error prone production.

2.8 A CBA example: whiplash protection

Based on a previous study, this chapter gives an example of a CBA of innovative car seats to protect from WAD in rear-end collisions. The seats were developed by Swedish car manufacturers Volvo and Saab and have become standard equipment in their cars. Their effectiveness in preventing WAD was evaluated by estimating the cost of developing and producing the seats. Subsequently, benefits were found to greatly exceed costs.

Some years ago, the Institute of Transport Economics and Molde University College jointly carried out a project for the Swedish Agency for Innovation (VINNOVA) on the benefits on neck injury research at Chalmers University of Technology in Gothenburg, Sweden, (Sandberg Eriksen, Hervik, Steen, Elvik, & Hagman, 2004). The study included an evaluation of benefits and costs of three whiplash protection systems developed by Autoliv, Saab and Volvo.

Autoliv developed a system called YSAB, Yieldable Seat Attachment Bracket, intended for retrofitting in cars. The system was fitted in 7,000 Toyota cars and was found to work as intended. The systems developed by Saab and Volvo were intended for newly manufactured cars. By the time of the study, it was estimated that about 250,000 Saab and Volvo cars in Sweden were equipped with either of these systems. The Saab system, SAHR, Saab Active Head Restraint, is based on the single weight-arm principle, by which the force of the back of the driver, being pushed against the seat back in a rear-end collision would move the head restraint forwards to capture the head before it was thrown back by the force of the rear-end impact. The Volvo seat, WHIPS, Whiplash Protection Seat, is based on a rearward translation of the seat back and a mechanism that upon a rear end impact would allow the seat to recline backwards to dampen the whiplash motion.

The three systems have been considered together in the CBA. Their effects on WAD were determined by means of a meta-analysis of five evaluation studies (Viano & Olsen, 2001); (Farmer, Wells, & Lund, 2003); (Krafft, Kullgren, Lie, & Tingvall, 2003); (Krafft, Kullgren, & Ydenius, 2004); (Jakobsson L. , 2004). Based on this analysis, the seats were assumed to reduce the probability of a slight WAD by 20% and the probability of a serious WAD by 50%.

Based on insurance records, the total number of whiplash injuries in Sweden per year was estimated to 20,000 slight injuries and 2,000 serious injuries in 4,000,000 cars. Applied to the 250,000 cars having the improved seats, this translated to a total of 1,250 slight and 125 serious whiplash injuries in one year.
The monetary valuation of benefits has been based on official monetary valuations of the prevention of traffic injury in Sweden at the time. These valuations, in Swedish Krona (SEK) were:

Injury severity	Value of prevention (SEK)
Fatal	17,511,000
Serious	3,124,000
Slight	175,000

For slight whiplash injuries, the value of SEK 175,000 was used. Preventing a serious whiplash injury has been valued at SEK 2,000,000, somewhat lower than the generic valuation of preventing a serious traffic injury.

It can be noted in passing, that at the time of this study, the disability weights for injuries proposed by the EUROCOST group (Haagsma et al. 2012) had still not been developed. The disability weight for a temporary (i.e. slight) WAD is, as noted above 0.073, corresponding to the loss of 0.073 years of perfect health. Using a 4 % discount rate and a remaining life expectancy of 40 years, the value of a life year, based on the value of preventing a fatality, can be estimated to SEK 884,840. Applying the EUROCOST disability weight, the value of preventing a slight WAD becomes about SEK 64,600 – considerably less than the SEK 175,000 applied in the CBA. Even this estimate may be too high, since values of QALYs derived from the VSL, as noted in Chapter 4, are considerably higher than the values obtained in stated preference survey asking people to value a QALY directly.

Annual benefits for the 250,000 cars having the improved seats were estimated as:

Slight injuries prevented: 1,250 · 0.20 · SEK 175,000 = SEK 43,750,000
Serious injuries prevented: 125 · 0.50 · SEK 2,000,000 = SEK 125,000,000

The first term is the annual number of injuries (1,250 slight, 125 serious). The second term is the effectiveness of the seats (20% reduction (0.20) of slight injuries, 50% reduction (0.50) of serious injuries). The third term is the valuation of the injuries (SEK 175,000 for a slight injury, SEK 2,000,000 for a serious injury).

The total annual benefit would be SEK 168.75 million. The present value of the benefits, assuming a car service life of 15 years and an annual discount rate of 4%, would be SEK 1,876 million.

Turning to the cost of the system, it was roughly estimated that the additional costs associated with manufacturing improved seats amounted to SEK 200 per car. For the 250,000 Saab and Volvo cars that had the system at the time of the study, total costs would then be SEK 50 million.

Development costs for Saab and Volvo were estimated to between SEK 1.2 and 2 million each year from 1994 to 2003. If an estimate of 1.6 million is applied, total cost for the 10 years reaches SEK 16 million. Publicly funded basic research preceding industrial innovation was estimated to have cost about SEK 53 million.

The Volvo seat needed repair after deployment in a crash. It is not known how many Volvo cars were involved in crashes needing seat repair, but one can conservatively assume 900 per year (based on the fact that Volvo sold more cars in Sweden than Saab). If repair cost are the same as the cost of retrofitting the YSAB system, SEK 1,000 per car, the total annual cost would be SEK 0.9 million. Discounted for a period of 10 years at a 4% annual discount rate, the present value would be SEK 7.3 million.

Rounding up, it was found that:

Benefits of whiplash protection seats:	SEK 1,876 million
Cost of whiplash protection seats: (50 + 16 + 53 + 7)	SEK 135 million

It is seen that even if a much lower monetary valuation of preventing a slight WAD had been adopted, benefits would exceed cost by a wide margin. The result is, therefore, very robust and there can be no doubt that benefits were greater than costs.

A similar example, but based on virtual testing and using the VIRTUAL CBA tool, can be found in Section 5.1.

2.9 Summary of recommendations

To enable CBA of innovative safety systems, the impacts of these systems on the number and severity of injuries must be quantified. The following recommendations are proposed in order to create a basis for CBA:

1. Quantification of impacts on injury

- For each safety system, identify the types of injuries it may affect (e.g. WAD, fractures when falling on board a public transport vehicle).
- Estimate the expected annual number of injuries per year per vehicle. For some types of injuries, this could be a very low number. Thus, in the example given in Section 2.8, the expected number of whiplash injuries per car (Volvo and Saab) per year was calculated as (1250 + 125)/250000 and resulted in 0.0055.
- Classify the expected number of injuries by severity. It is proposed, viz. the EUROCOST system, to use only two levels of severity: injuries that heal completely and injuries that result in permanent impairment. This is because the EUROCOST system has these two levels of severity and corresponding disability weights. It is recognised that this is crude and that any permanent impairment can be small or large. However, the disability weights developed in EUROCOST should be interpreted as mean values covering the full spectrum of degrees of permanent impairment. In

addition, the Maximum Abbreviated Injury Scale (MAIS) categorisation can be applied to assess injury severity in more detail.
- Estimate the impact of a new safety system as the percentage change in the expected number of injuries per vehicle per year by injury severity (because expected impacts may vary according to in jury severity).

2. Conversion of impacts to QALYs by means of EUROCOST

Impacts stated as changes in the expected number of injuries coded by means of ICD can be mapped onto the injury diagnoses listed in EUROCOST. Injuries should be classified as either temporary or lifelong. For injury diagnoses not listed in EUROCOST, the disability weights used in the Global Burden of Disease study (World Health Organization (WHO), 2004) could be used.

3. Fixed parameters for CBA

The fixed parameters for analysis include the time horizon, the discount rate and the valuation of preventing injuries.

It is proposed to use a time horizon of 15 years for cars, 10 years for buses and 30 years for trams.

It is proposed to use an annual discount rate of 3%. This rate will be applied both to future (quality adjusted) years of life and to future costs and benefits.

A monetary value of a QALY, with a range of uncertainty, has been proposed in Section 2.3 (€70,000).

4. Sensitivity analyses

It is proposed to perform sensitivity analyses with respect to the cost of innovative safety systems, as these are not well known and not available in the form of an interval.

It is further proposed to perform sensitivity analyses with respect to the impact of safety systems on injuries. The minimum amount of uncertainty in these estimates will equal random variation in the expected number of injuries prevented, which can be estimated by relying on the Poisson probability model.

It is proposed to perform sensitivity analyses with respect to the monetary valuation of prevented injuries, as indicated above.

The sensitivity analyses should be performed component by component, as the joint probability distribution of the factors is unknown.

3 VIRTUAL CBA tool

This chapter explains in detail how the VIRTUAL CBA tool is structured and its functions in the background. Suggestions from the guidelines in Chapter 2 have been applied. The chapter is based on Milestones M6.2 (Preliminary cost-benefit tool of automotive safety) and M6.3 (Description of the preliminary tool for CBA and preliminary guidelines for users of the tool). The explanations were adapted to the final CBA tool.

3.1 The VIRTUAL CBA tool

Figure 2 shows the structure of the VIRTUAL CBA tool in terms of inputs and outputs with respect to the benefits and the costs. The tool uses several types of inputs:

- Inputs that are different for each safety system, such as the cost and safety impact of the safety system.
- Inputs that are the same for each safety system but different across countries. Examples are life expectancy and vehicle lifetime.
- Parameters that are (assumed to be) the same for each safety system and each country. These are inputs required to calculate QALY gains (injury disability weights and injury duration) and monetary valuations.

The first two types of inputs are to be completed by the user of the tool (user inputs), whereas fixed parameters cannot be altered by users. The tool calculates all costs and benefits on a per vehicle basis. Consequently, all inputs should refer to a single vehicle.

The benefits of implementing a (new) safety system are quantified in terms of the number of injuries prevented, reduction of injury severity and the related monetary valuation. For this calculation, the number of injuries prevented by injury group and gender are calculated. The tool uses the EUROCOST injury classification system which distinguishes 39 injury groups (Haagsma, et al., 2012). Male and female injury reductions are calculated separately because the effectiveness of safety systems can differ between men and women and HBMs allow taking into account these differences. The number of injuries prevented are subsequently translated into impact on quality of life (QALYs, see below) and monetary units. This is done in a number of steps:

1. The number of injuries before and after implementation of the safety system (by injury group and gender) are calculated using the crash risks with and without the safety system, the probabilities of sustaining a specific injury if a crash occurs with and without the system (by gender), the number of target road users (vehicle occupants or other road users involved in a collision) the safety system affects and the proportions of male and female road users. Note that the crash risks before and after the implementation are equal in case of safety systems aimed at only reducing the severity of injuries (passive safety). The initial number of injuries is an intermediate output, which the tool does not present as final output as indicated by the dashed line of this box in Figure 2.
2. The reduction of the number of injuries is calculated as the difference between the number of injuries before and after implementation of the safety system.
3. The yearly reduction of the number of injuries is translated into QALYs. QALYs are a measure for the impact on quality of life that combines injury severity and the duration of the (health impact) of an injury. The number of QALYs is calculated using injury disability weights and injury duration. Disability weights reflect the impact of an injury on quality of life. The duration of injuries with

lifelong health consequences is calculated using the age and life expectancy of the involved persons.

4. Total QALY gains per vehicle are calculated using the yearly QALY gains and the lifetime of the vehicle.
5. QALY gains are translated into monetary benefits using a monetary valuation per QALY. In addition, reductions of medical costs and production loss resulting from preventing injuries are included in the monetary benefits.
6. A discount rate is applied to account for the common practice in CBA to assign a lower weight to benefits if they occur further in the future (see Chapter 2). By applying discounting, the present value of the monetary benefits is determined.

The number of vehicles in which the safety system needs to be implemented to prevent one injury and to gain one QALY is calculated as an additional result (not depicted in Figure 2). This output may be easier to interpret since the number of injuries prevented and the corresponding QALY gains per vehicle may be very small (as shown by the example in Section 3.2).

The inputs that the tool uses on the cost side include the cost of developing and manufacturing the safety system as well as the cost of repairing or replacing the safety system if it has been deployed in a crash. The repair/replacement costs are calculated using the crash risk after implementation of the safety system, using the initial crash risk and crash risk reduction as inputs. Any future costs of repairing or replacing the safety system, which may occur sometime during the lifetime of a vehicle, are translated into present values using the vehicle lifetime and the discount rate.

A comparison of costs and benefits is made by calculating the net present value, which is the balance of the benefits and the costs, and the ratio of benefits and the costs (all in present values). A positive net present value, or a benefit-cost ratio greater than one, indicates that implementing the safety system is profitable from a socio-economic point of view.

Figure 2 Overview of the VIRTUAL cost-benefit tool

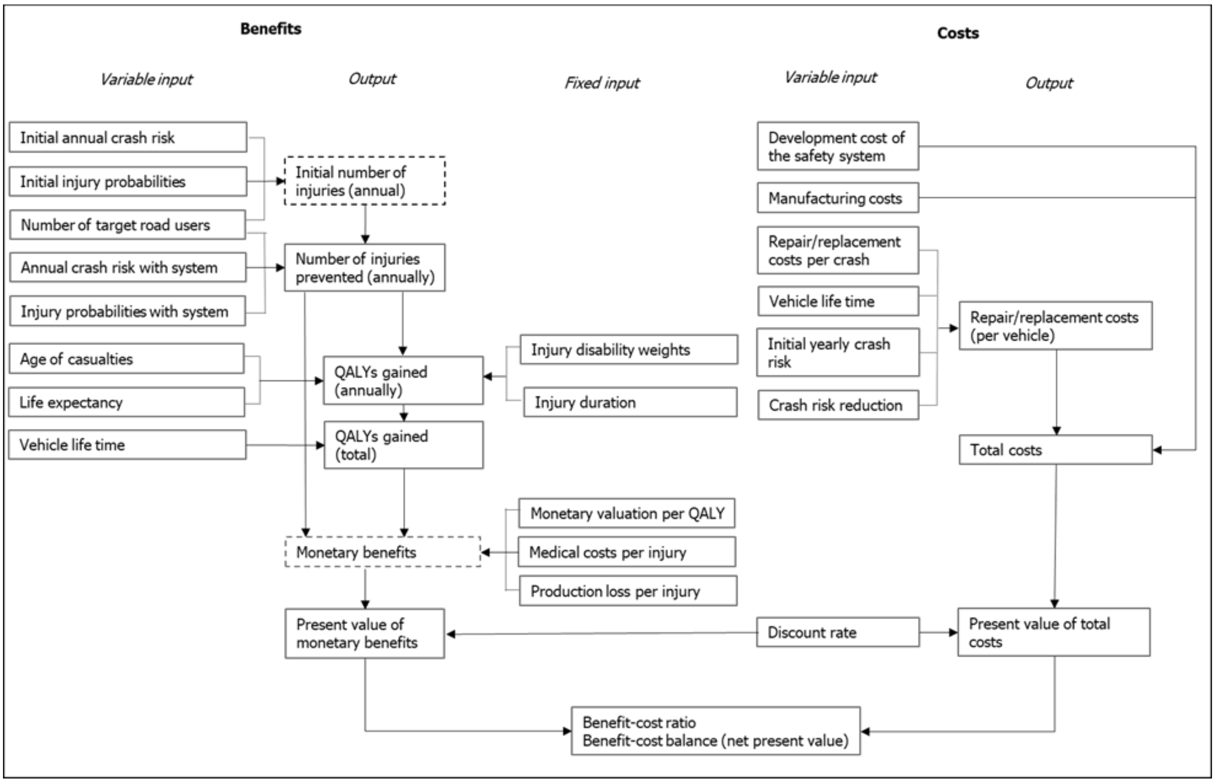


Figure 3 shows the main sheet of the VIRTUAL CBA tool as developed in MS Excel. On the left-hand side of the tool, users can insert all required input data (yellow shaded). Fixed inputs (which cannot be altered by the user) are not shown on this sheet. For each parameter, the user can insert a best estimate as well as an upper and lower value to reflect uncertainty in the input data. The sheet shown here includes the data for the example of improved seats for whiplash prevention as presented in Section 3.2. The best estimates refer to the data discussed in that section. The upper and lower values are arbitrary values for the sake of illustration.

The right-hand side of this sheet shows the outputs of the CBA, including the safety impacts, monetary benefits and ratio and balance of benefits and costs. The tool allows accounting for uncertainty in input data by giving users the opportunity to insert upper and lower input values, in addition to best estimates. Accordingly, the tool calculates best estimates as well as upper and lower limits for all outputs.

Figure 3 Main sheet of the CBA tool

COST-BENEFIT TOOL FOR VEHICLE SAFETY

Measure: Active headrest

Input

	lower	best estimate	upper
Costs per vehicle			
· Development costs	€ 15	€ 20	€ 25
· Manufacturing costs	€ 10	€ 15	€ 20
· Repair/replacement costs after a crash	€ 50	€ 78	€ 100
Crash risk (number of target crashes per vehicle per year)			
· before intervention	0,012	0,012	0,012
· after intervention	0,012	0,012	0,012
Road user characteristics			
· Number of target road users per vehicle		1	
· Average age casualties: · male		40	
· female		40	
· Life expectancy: · male		78	
· female		83	
· Proportion male target road user		60%	
Vehicle life time (years)		15	
Discount rate		3,0%	

Results

	lower	best estimate	upper
Total costs	€ 32	€ 47	€ 60
Number of injuries prevented			
· Yearly	0,0005	0,0013	0,0026
· Total vehicle lifetime	0,008	0,020	0,039
· 1 injury prevented per ... vehicles	126	51	26
Quality of life improvement (QALYs)			
· Yearly	0,0003	0,0007	0,0015
· Total vehicle lifetime	0,004	0,011	0,022
· 1 QALY gained per ... vehicles	225	90	46
Benefits			
· Quality of life gains	€ 247	€ 622	€ 1.220
· Medical costs reduction	€ 24	€ 59	€ 116
· Productivity gains	€ 117	€ 294	€ 577
· Total benefits	€ 388	€ 975	€ 1.913
Socio-economic return			
· Net present value	€ 329	€ 928	€ 1.880
· Benefit-cost ratio	6	21	59

In addition to the inputs in the main sheet shown in Figure 3, users must fill in data on injury probabilities and injury probability reduction in an additional sheet. Figure 4 shows an excerpt of this sheet for the whiplash example.

Figure 4 Input sheet for injury probabilities, categorised in male and female, before and after intervention as well as lower, best and upper estimate.

INPUT INJURY PROBABILITIES

	Injury group	**Injury probability**											
		Male						**Female**					
		before intervention			***after intervention***			***before intervention***			***after intervention***		
		lower	*best estimate*	*upper*	*lower*	*best estimate*	*upper*	*lower*	*best estimate*	*upper*	*lower*	*best estimate*	*upper*
1	Concussion												
2	Other skull–brain injury												
3	Open wound on head												
4a	Eye injury - left												
4b	Eye injury - right												
5	Fracture of facial bone(s)												
6	Open wound on face												
7	Fracture/dislocation/sprain/strain of vertebrae/spine												
8	Whiplash injury/sprain of cervical spine	30%	40%	50%	26%	31%	32%	45%	60%	75%	40%	46%	48%
9	Spinal-cord injury												
10	Internal-organ injury												

Furthermore, the tool contains a sheet with the definition or brief explanation of the inputs and outputs (Figure 5).

Figure 5 Definitions and explanation of inputs and outputs

Definitions and explanation of inputs and outputs

All inputs and outputs are per vehicle

Item	**Definition/explanation**
Inputs	
Number of target road user per vehicle	Number of road users per vehicle who are affected by the safety system
Development costs	Cost of developing the vehicle safety system (research, testing, etc.). These costs may be reflected in the market price of the system
Manufacturing costs	Cost of manufacturing vehicle safety system. These costs may be reflected in the market price of the system.
Repair/replacement costs after a crash	Cost of repairing or replacing the system after deployment in a crash
Crash risk before/after intervention	Number of target crashes per vehicle per year before/after implementation of the safety system. Target crashes are crashes which are affected by the safety system.
Average age casualties	Average age of casualties affected by the safety system (male/female)
Life expectancy	Life expectancy of casualties affected by the safety system (male/female)
Proportion male road users	Proportion of male road users affected by the safety system
Vehicle life time	Average number of years a vehicle is used on the road
Discount rate	Percentual rate at which future cost and benefits are discounted, reflecting the fact that costs and benefits have a lower weight if they occur further in the future. The EC recommends 3% for non-cohesion countries and 5% for cohesion countries.
Outputs	
Total costs	Present value of the sum of development costs, manufacturing costs and discounted repair/replacement costs
Number of injuries prevented	
- Yearly	Yearly number of injuries prevented by the safety system, summed over all injury types
- Total vehicle lifetime	Number of injuries prevented by the safety system during the vehicle life time, summed over all injury types
- 1 injury prevented per ... vehicles	Number of vehicles in which the safety system needs to be implemented to prevent one injury
Quality of life improvement (QALYs)	
- Yearly	Yearly number of QALYs gained by the safety system. QALYs represent quality of life loss, reflecting severity and duration of injuries.
- Total vehicle lifetime	Number of QALYs gained by the safety system during the vehicle life time
- 1 QALY gained per ... vehicles	Number of vehicles in which the safety system needs to be implemented to prevent one QALY
Quality of life gains	Present value of the monetised QALY gains. The present value is the sum of the discounted yearly monetary benefits.
Medical costs reduction	Present value of reduced costs of medical treatment of road casualties due to the safety system
Productivity gains	Present value of reduced loss of productivity of road casualties due to the safety system
Total benefits	Sum of the quality of life gains, medical cost reduction and productivity gains
Net present value	Total benefits minus total costs
Benefit-cost ratio	Total benefits divided by total costs

3.2 The CBA calculation model in closer detail

3.2.1 Intervention to be evaluated and baseline scenario

To conduct a CBA, the intervention to be evaluated should be clearly defined and described. In the VIRTUAL project, the interventions concern implementation of vehicle safety systems (see Table 1). To facilitate assessment of the costs and benefits of implementing a safety system, a baseline scenario should be defined. The costs and benefits of the safety system will be assessed as compared to the baseline scenario. The baseline scenario can consist of a status quo (in case of vehicle safety systems, (e.g. no changes to a vehicle in case the vehicle systems are being studied) or a scenario that includes continuation of current developments and policies (e.g. increased penetration of certain safety systems that reduce injury risk in addition to the impact of the safety system under consideration).

Example

Saab and Volvo have developed systems to reduce the risk of WAD in rear-end crashes (see example in Chapter 2.8). It was estimated that about 250,000 Saab and Volvo cars in Sweden were equipped with such a system in 2004. The Saab system, Saab Active Head Restraint, was based on the single weight-arm principle, by which the force of the back of the driver, being pushed against the seat back in a rear-end collision would move the head restraint forwards, to capture the head before it was thrown back by the force of the rear-end impact. The Volvo seat system, Whiplash Protection System, included an energy-absorbing recliner mechanism, which enabled the seat back to move to some extent with the occupant rearward during a rear-end impact (Jakobsson L. , 2007). A CBA of these systems was conducted by the Institute of Transport Economics and Molde University College (Sandberg Eriksen, Hervik, Steen, Elvik, & Hagman, 2004). The baseline scenario was the status quo situation, which implies that the costs and benefits of the systems were assessed as compared to the same vehicle without the system and without any other changes.

3.2.2 Number of injuries prevented

The number of injuries prevented is calculated on the basis of the number of target road users, proportion of male and female target road users, the crash risk and the injury probability if a crash occurs before and after implementation of the safety system. This is done in the following steps:

1. The annual number of injuries per vehicle before implementation of the safety system is calculated on the basis of the number of road users each safety system affects by gender, the initial crash risk (defined as the annual number of crashes per vehicle) and injury probability before the intervention by injury group and gender (Equation (1)). Following Haagsma et al. (Haagsma, et al., 2012), 39 injury groups are distinguished. A distinction is made between left and right body parts if applicable.
2. The annual number of injuries per vehicle after implementation of the safety system is calculated in a similar way, using the number of road users each safety system affects by gender, the crash risk after the intervention and injury probability after the intervention by injury group and gender (Equation (2)).
3. The annual number of prevented injuries is calculated as the difference between the number of injuries before and after implementation of the safety system, summed over all injury groups and gender (Equation (3)).
4. The total number of injuries prevented per vehicle is calculated on the basis of vehicle lifetime (Equation (4)). Note that the number of injuries prevented may not be equal to the number of injured casualties if the safety system prevents more than one injury group.

The data on the number of target road users, crash risk, injury probabilities and vehicle lifetime need to be entered by the users of the tool.

(1) $I_{0,ig,g} = RU_g * R_0 * P_{0,ig,g}$

where:

RU_g = Number of target road users the intervention affects by gender

$I_{0,ig,g}$ = Annual number of injuries before intervention, by injury group (*ig*) and gender (*g*)

R_0 = Annual target crash risk before intervention

$P_{0,ig,g}$ = Injury probability before intervention, by injury group and gender

(2) $I_{1,ig,g} = RU_g * R_1 * P_{1,ig,g}$

where:

$I_{1,ig,g}$ = Annual number of injuries after intervention, by injury group and gender

R_1 = Annual target crash risk after intervention

$P_{1,ig,g}$ = Injury probability after intervention, by injury group and gender

(3) $AIP = \sum_{it=1}^{it=39}(I_{1,ig,m} - I_{0,ig,m}) + \sum_{it=1}^{it=39}(I_{1,ig,f} - I_{0,ig,f})$

where:

AIP = Annual number of injuries prevented

$I_{1,ig,m}$ = Annual number of male injuries after intervention, by injury group (*ig*)

$I_{0,ig,m}$ = Annual number of male injuries before intervention, by injury group

$I_{1,ig,f}$ = Annual number of female injuries after intervention, by injury group

$I_{0,ig,f}$ = Annual number of female injuries before intervention, by injury group

(4) IP = AIP * VLT

where:
IP = Number of injuries prevented
VLT = Vehicle lifetime

Example
Based on insurance records, the total number of WADs in Sweden was estimated at 22,000 per year (2,000 serious and 20,000 slight injuries, see Section 2.8), which translates into 0.006 injuries per car per year (the number of cars in Sweden was 4,000,000, source: Eurostat 2022). We assume that the target crash risk (R_0) was 0.012 and the initial probability of WAD was 40% for men ($P_{0,\ whiplash,m}$) and 60% for women ($P_{0,\ whiplash,f}$). The improved seat was estimated to reduce the probability of WAD by 23%, which implies that the WAD probability after the intervention is 31% for men ($P_{1,\ whiplash,m}$) and 46% for women ($P_{1,\ whiplash,f}$). The crash risk is not influenced by the improved seat, which implies that the crash risk after the intervention (R_1) is 0.012 (equal to R_0). The number of target road users (occupants) per car is 1, as the analysis refers to one seat per car. It is assumed that 60% of the target occupants are men which implies that the number of male and female target occupants (RU_m and RU_f) are both 0.6 and 0.4, respectively. Using equations (1)-(3), the resulting annual number of WAD prevented is 0.0013 per car. Assuming a vehicle lifetime (VLT) of 15 years, the total number of prevented WAD (AIP) per car is 0.020, which translates into one injury per 51 cars.

The user input and results are highlighted in Figure 6 and Figure 7.

If information on the type of injuries that are prevented is not available, the tool offers the option to insert only the number of injuries by severity instead of by injury group. In that case, the user can enter the initial probabilities of a fatal, serious and slight injury and the percentual reduction of these probabilities (where a serious injury is defined as an injury that requires hospital admission; all other injuries are defined as slight).

Figure 6 User input for calculating the number of injuries prevented and results

COST-BENEFIT TOOL FOR VEHICLE SAFETY

virtual

Measure: Active headrest

Input

	lower	best estimate	upper
Costs per vehicle			
- Development costs	€ 15	€ 20	€ 25
- Manufacturing costs	€ 10	€ 15	€ 20
- Repair/replacement costs after a crash	€ 50	€ 78	€ 100
Crash risk (number of target crashes per vehicle per year)			
- before intervention	0,012	0,012	0,012
- after intervention	0,012	0,012	0,012
Road user characteristics			
- Number of target road users per vehicle		1	
- Average age casualties: - male		40	
- female		40	
- Life expectancy: - male		78	
- female		83	
- Proportion male target road user		60%	
Vehicle life time (years)		15	
Discount rate		3,0%	

Results

	lower	best estimate	upper
Total costs	€ 32	€ 47	€ 60
Number of injuries prevented			
- Yearly	0,0005	0,0013	0,0026
- Total vehicle lifetime	0,008	0,020	0,039
- 1 injury prevented per ... vehicles	126	51	26
Quality of life improvement (QALYs)			
- Yearly	0,0003	0,0007	0,0015
- Total vehicle lifetime	0,004	0,011	0,022
- 1 QALY gained per ... vehicles	225	90	46
Benefits			
- Quality of life gains	€ 247	€ 622	€ 1.220
- Medical costs reduction	€ 24	€ 59	€ 116
- Productivity gains	€ 117	€ 294	€ 577
- Total benefits	€ 388	€ 975	€ 1.913
Socio-economic return			
- Net present value	€ 329	€ 928	€ 1.880
- Benefit-cost ratio	6	21	59

Figure 7 Injury probability input

INPUT INJURY PROBABILITIES

	Injury group	Injury probability Male before intervention lower	best estimate	upper	after intervention lower	best estimate	upper	Female before intervention lower	best estimate	upper	after intervention lower	best estimate	upper
1	Concussion												
2	Other skull–brain injury												
3	Open wound on head												
4a	Eye injury - left												
4b	Eye injury - right												
5	Fracture of facial bone(s)												
6	Open wound on face												
7	Fracture/dislocation/sprain/strain of vertebrae/spine												
8	Whiplash injury/sprain of cervical spine	30%	40%	50%	26%	31%	32%	45%	60%	75%	40%	46%	48%
9	Spinal-cord injury												
10	Internal-organ injury												

3.2.3 Quality Adjusted Life Years (QALYs)

The number of QALYs gained is calculated using the number of injuries prevented, disability weights that reflect the severity of the injuries and the impact on quality of life, and the duration of the loss of quality of life. The method developed by Haagsma et al., is used to calculate QALY gains (Haagsma, et al., 2012). This method distinguishes between injuries that are treated only at the emergency department (ED) of a hospital and injuries that require hospital admission (HDR)[2]. Concerning the duration of quality-of-life loss, a distinction is made between the acute phase and lifelong injury consequences. For the acute phase, the injury duration is set at 1 year and lifelong consequences sustained during all remaining life years. QALY gains concerning the acute phase are calculated using the number of injuries prevented (by injury group), the proportion of injuries treated only at the ED versus hospital admission (in-patient) and disability weights for the acute phase (separately for ED an HDR), see Equation (5).

(5) $\mathrm{QALY_{ac}} = \sum_{\mathrm{ig}=1}^{\mathrm{ig}=39} (\mathrm{AIP_{ig}} * \mathrm{ID} * ((1 - \mathrm{LC_{ED,ig}}) * (1 - \mathrm{HDR_{ig}}) * \mathrm{DW_{acED,ig}} + (1 - LC_{HDR,ig}) * HDR_{ig} * \mathrm{DW_{acHDR,ig}}))$

where:

$\mathrm{QALY_{ac}}$ = Number of QALYs gained in the acute injury phase (first year)
ID = Injury duration in the acute phase
$\mathrm{LC_{ED,ig}}$ = Proportion of ED-injuries with lifelong impact on quality of life, by injury
$\mathrm{HDR_{ig}}$ = Proportion of in-patient injuries, by injury group
$\mathrm{DW_{acED,ig}}$ = Disability weight for the acute phase of injuries treated only at the emergency department, by injury group
$\mathrm{LC_{HDR,ig}}$ = Proportion of HDR-injuries with lifelong impact on quality of life, by injury group
$\mathrm{DW_{acHDR,ig}}$ = Disability weight for the acute phase of in-patient injuries, by injury group

Note that injuries either have an acute impact on quality of life (1 year) or lifelong (including the first year). Consequently, the proportion of injuries with only acute impact on quality of life are calculated as (1- $\mathrm{LC_{ED,ig}}$/100). Similarly, the number of injuries treated at the emergency department is calculated as (1 – $\mathrm{HDR_{ig}}$/100), as they are either treated at the emergency department or through hospital admission.

Concerning lifelong injury consequences, the number of QALYs gained is calculated on the basis of the number of injuries prevented, remaining life years, the proportion of injuries with lifelong injury consequences (separately for ED and HDR injuries) and disability weights for lifelong consequences. This is done separately for men and women because the life expectancy, and possibly the age of the target road user, differ for men and women (Equation ((6)).

[2] Following Haagsma et al. (2012), we use the abbreviation (HDR) Hospital Discharge Register for hospital admissions.

$$(6)\ QALY_L = \sum_{ig=1}^{ig=39}(AIP_{ig,m} * (LE_m - AGE_m) * DW_{L,ig} * (LC_{ED,ig} * (1 - HDR_{ig}) + LC_{HDR,ig} * HDR_{ig})) + \sum_{ig=1}^{ig=39}(AIP_{ig,f} * (LE_f - AGE_f) * DW_{L,ig} * (LC_{ED,ig} * (1 - HDR_{ig}) + LC_{HDR,ig} * HDR_{ig}))$$

where:

$QALY_L$	= Number of QALYs gained by preventing lifelong injury consequences
AIP_m	= Annual number of male injuries prevented
LE_m	= Male life expectancy
AGE_m	= Average age of prevented male casualties
AIP_f	= Annual number of female injuries prevented
LE_f	= Female life expectancy
AGE_f	= Average age of prevented female casualties
$DW_{L,ig}$	= Disability weight for life long injuries treated only at the ED, by injury group

The total number of QALYs gained per vehicle is calculated as follows:

$$(7)\ QALY_{tot} = (QALY_{ac} + QALY_{ll}) * VLT$$

Example
The improved seat is estimated to prevent 0.0014 WAD per car per year. Based on the number of WADs in Sweden, we assume that 10% of WADs require hospital admission ($HDR_{whiplash}$ = 0.1) and that 90% is only treated at an ED. The disability weight for the acute phase of WAD that are (only) treated at the ED is 0.073. This represents a 7.3% quality-of-life loss as compared to perfect health. A disability weight for HDR-injuries is not available, but for this example we have assumed that this disability weight is also 0.073 (as a minimum). Furthermore, it is assumed that the proportion of casualties with lifelong health consequences is 17% for both HDR and ED casualties ($LC_{HDR,whiplash}$= $LC_{ED,whiplash}$= 0.17).

Furthermore, we have assumed that the average age of casualties is 40 years and life expectancy is 78 years for men and 83 years for women. These data and assumptions are taken from the case study in Section 5.1.
Using Equations (5) and (6) this results in 0.0007 QALYs gained per vehicle per year and 0.011 per car in total (using a vehicle lifetime of 15 years). This equals one QALY gain per 90 cars.

Figure 8 User input for calculating QALYs and results

COST-BENEFIT TOOL FOR VEHICLE SAFETY

virtual

Measure: Active headrest

Input

	lower	*best estimate*	*upper*
Costs per vehicle			
- Development costs	€ 15	€ 20	€ 25
- Manufacturing costs	€ 10	€ 15	€ 20
- Repair/replacement costs after a crash	€ 50	€ 78	€ 100
Crash risk (number of target crashes per vehicle per year)			
- before intervention	0,012	0,012	0,012
- after intervention	0,012	0,012	0,012
Road user characteristics			
- Number of target road users per vehicle		1	
- Average age casualties: - male		40	
- female		40	
- Life expectancy: - male		78	
- female		83	
- Proportion male target road user		60%	
Vehicle life time (years)		15	
Discount rate		3,0%	

Results

	lower	*best estimate*	*upper*
Total costs	€ 32	€ 47	€ 60
Number of injuries prevented			
- Yearly	0,0005	0,0013	0,0026
- Total vehicle lifetime	0,008	0,020	0,039
- 1 injury prevented per ... vehicles	126	51	26
Quality of life improvement (QALYs)			
- Yearly	0,0003	0,0007	0,0015
- Total vehicle lifetime	0,004	0,011	0,022
- 1 QALY gained per ... vehicles	225	90	46
Benefits			
- Quality of life gains	€ 247	€ 622	€ 1.220
- Medical costs reduction	€ 24	€ 59	€ 116
- Productivity gains	€ 117	€ 294	€ 577
- Total benefits	€ 388	€ 975	€ 1.913
Socio-economic return			
- Net present value	€ 329	€ 928	€ 1.880
- Benefit-cost ratio	6	21	59

3.2.4 Monetary benefits

To calculate the benefits, QALY gains are translated into monetary units using a value per QALY and estimates of the medical costs and productivity loss per injury. The value of quality-of-life loss is set at €70,000 per QALY (see Section 2.3).

Reduction in medical costs and production losses are calculated using the number of injuries prevented and values per injury type, separately for ED and HDR injuries. For the purpose of this study, the medical costs and productivity losses for ED and HDR road casualties by injury type were provided by the Dutch Consumer Safety Institute, based on the Dutch Cost of Injury Model (Polinder, et al., 2016). Since these data only cover the costs in the first year after the injury, a standardised European figure of productivity loss per serious injury from Wijnen et al. (Wijnen, et al., 2017) was used additionally to account for long term productivity losses. The average medical costs are €2.128 and €10.918 for ED and HDR casualties, respectively, and the productivity loss €3,863 and €47,000 respectively. Average medical costs and production loss for ED and HDR casualties, weighted by the number of ED and HDR casualties are used in the calculation tool.

Monetary benefits in future years are discounted using a discount rate that reflects that costs and benefits have a lower weight if they occur further in the future. The present value of monetary benefits during the vehicle lifetime is calculated using the total QALY gains and the value per QALY as well as the number of injuries prevented and the medical costs and production loss by injury group. In addition, a yearly discount factor 1/(1+r) is used:

$$(8)\ \mathrm{B} = \sum_{t=0}^{t=VLT} \left(\frac{1}{(1+\mathrm{r})^{\mathrm{t}}}\right) * (\mathrm{QALY} * \mathrm{VQ} * + \sum_{it=39}^{it=1} (AIP_{ig} * (MC_{ig} + PL_{ig})))$$

where:

B = Present value of the monetary benefits
QALY = Annual QALY gains
VQ = Monetary value per QALY

t = Year
r = Discount rate
MC_{ig} = Medical cost per injury by injury group
PL_{ig} = Production loss per injury by injury group

Note that the number of QALYs gained is assumed to be constant during the vehicle life, which implies that the total number of QALYs gained can be multiplied by the discount factor that is included in Equation (8) (instead of discounting the benefits in year t by a factor $1/(1+r)^t$ and then sum the yearly benefits, which is the common practice in CBA).

In case information on injury groups is missing and the safety impacts are expressed in terms of the number of casualties prevented by severity (fatality, serious injury and slight injury), the benefits are calculated using the monetary valuation of per casualty prevented, instead of the value per QALY. Standardised European values as developed by Wijnen et al. (2017) are used for this calculation (Wijnen, et al., 2017). The value per fatality, serious injury and slight injury is €2.4 million, €319,000 and €29,000, respectively (Source: (Wijnen, et al., 2017), updated for inflation using harmonised consumer price index from Eurostat).

Example
The monetary benefit of preventing WAD by the improved seats is calculated using the annual QALY gains (0.0003 per car), the monetary value of a QALY (€70,000), medical costs and production loss per WAD (€22,000) and the discount rate (set at 3%). From Equation (8) follows that the present value of the monetary benefits is €975 per car. About two thirds of the €622 benefits are quality of life gains, while productivity gains account for €294. Medical costs reductions are estimated at €59.

Figure 9 User input for calculating socio-economic beneifits and results

COST-BENEFIT TOOL FOR VEHICLE SAFETY

Measure: Active headrest

Input

	lower	*best estimate*	*upper*
Costs per vehicle			
- Development costs	€ 15	€ 20	€ 25
- Manufacturing costs	€ 10	€ 15	€ 20
- Repair/replacement costs after a crash	€ 50	€ 78	€ 100
Crash risk (number of target crashes per vehicle per year)			
- before intervention	0,012	0,012	0,012
- after intervention	0,012	0,012	0,012
Road user characteristics			
- Number of target road users per vehicle		1	
- Average age casualties: - male		40	
- female		40	
- Life expectancy: - male		78	
- female		83	
- Proportion male target road user		60%	
Vehicle life time (years)		15	
Discount rate		3,0%	

Results

	lower	*best estimate*	*upper*
Total costs	€ 32	€ 47	€ 60
Number of injuries prevented			
- Yearly	0,0005	0,0013	0,0026
- Total vehicle lifetime	0,008	0,020	0,039
- 1 injury prevented per ... vehicles	126	51	26
Quality of life improvement (QALYs)			
- Yearly	0,0003	0,0007	0,0015
- Total vehicle lifetime	0,004	0,011	0,022
- 1 QALY gained per ... vehicles	225	90	46
Benefits			
- Quality of life gains	€ 247	€ 622	€ 1.220
- Medical costs reduction	€ 24	€ 59	€ 116
- Productivity gains	€ 117	€ 294	€ 577
- Total benefits	€ 388	€ 975	€ 1.913
Socio-economic return			
- Net present value	€ 329	€ 928	€ 1.880
- Benefit-cost ratio	6	21	59

3.2.5 Costs

Three types of costs are distinguished in the CBA tool:

1. Cost of developing innovative safety systems.
2. Additional cost of manufacturing innovative safety systems.
3. Cost of repairing or replacing safety systems that have been deployed in crashes.

Users of the tool should enter estimates of the three types of costs per vehicle. The base year and price level of the tool is for 2018, so costs should also be expressed at the 2018 price level. In general, market prices of the relevant safety system can be used as a proxy for the manufacturing costs. Development costs are likely to be incorporated in the market price; in that case, a separate estimate of such costs is not required. Similarly, the cost of repairing/replacing the safety system can be estimated using the market price for repair/replacement. It is recognised that estimating these costs, in particular development costs, can be complicated. In such cases, educated guesses or stipulated costs may be used. See Chapter 2 for more explanation on costs related to safety systems.

Equations (9)-(10) summarise the cost calculations in the tool. Note that the cost of repairing or replacing a safety system can occur during the vehicle lifetime and these costs are discounted through a discount rate. The tool calculates the average repair/replacement cost per vehicle (RC) using the probability of a crash (after the intervention) during the vehicle lifetime and the cost per vehicle. The probability of a crash is calculated by multiplying the annual crash risk by the vehicle lifetime. The repair/replacement costs are discounted, assuming that the costs occur halfway through the lifetime of the vehicle:

(9) $C = DC + MC + RC$

(10) $RC = SRC * R_1 * VLT * 1/(1+r)^{VLT/2}$

where:
C = Total costs
DC = Development costs
MC = Manufacturing costs
RC = Repair and replacement costs
SRC = Cost of a single repair or replacement

Example
The average cost of developing the whiplash prevention systems were estimated at about SEK 69 million in the period 1994-2003: SEK 16 million for car manufactures and SEK 53 million for publicly funded basic research preceding industrial innovation. This translates into SEK 67 million at the 2018 price levels (using the harmonised price index for motor cars from Eurostat) or €5.0 million (using purchasing power parities for individual consumption from Eurostat [3]). The number of vehicles with the improved seat was estimated at 250,000, so the development cost per vehicle (DC) is €20. Any additional costs associated with manufacturing improved seats (MC) amounted to SEK 200 per car (2000 prices), which is €15 (2018 prices). Repair costs after deployment are estimated at SEK 1,000 per seat (2003 prices), which translates into €77 (2018 prices). Based on an annual crash risk of 0.012 (R_0=0.012), a vehicle lifetime of 15 years and a 3% discount rate, the repair cost per vehicle (RC) is estimated at €11. The total cost per vehicle is €47.

[3] Purchasing power parities take into account the exchange rate and relative income differences. This implies that the value is corrected for purchasing power differences between Sweden and the EU average.

Figure 10 User input for calculating costs of the safety system and result

COST-BENEFIT TOOL FOR VEHICLE SAFETY

Measure: Active headrest

Input

	lower	*best estimate*	*upper*
Costs per vehicle			
- Development costs	€ 15	€ 20	€ 25
- Manufacturing costs	€ 10	€ 15	€ 20
- Repair/replacement costs after a crash	€ 50	€ 78	€ 100
Crash risk (number of target crashes per vehicle per year)			
- before intervention	0,012	0,012	0,012
- after intervention	0,012	0,012	0,012
Road user characteristics			
- Number of target road users per vehicle		1	
- Average age casualties: - male		40	
- female		40	
- Life expectancy: - male		78	
- female		83	
- Proportion male target road user		60%	
Vehicle life time (years)		15	
Discount rate		3,0%	

Results

	lower	*best estimate*	*upper*
Total costs	€ 32	€ 47	€ 60
Number of injuries prevented			
- Yearly	0,0005	0,0013	0,0026
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- 1 injury prevented per … vehicles	126	51	26
Quality of life improvement (QALYs)			
- Yearly	0,0003	0,0007	0,0015
- Total vehicle lifetime	0,004	0,011	0,022
- 1 QALY gained per … vehicles	225	90	46
Benefits			
- Quality of life gains	€ 247	€ 622	€ 1.220
- Medical costs reduction	€ 24	€ 59	€ 116
- Productivity gains	€ 117	€ 294	€ 577
- Total benefits	€ 388	€ 975	€ 1.913
Socio-economic return			
- Net present value	€ 329	€ 928	€ 1.880
- Benefit-cost ratio	6	21	59

3.2.6 Benefit-cost ratio and net present value

The benefit-cost ratio (BCR) is defined as the ratio of the present values of the monetary benefits and costs:

(11) BCR = B/C

Implementation of a safety system is profitable from a socio-economic point of view if the BCR is greater than one.

The net present value (NPV) is defined as the difference between the present values of the benefits and costs:

(12) NPV = B – C

Implementation of a safety system is profitable from a socio-economic point of view if the NPV is positive.

Example

The benefits of the improved seat amount to €342 and the costs to €46 (present values). This results in a BCR of 21 and a NPV of €928. Clearly, the benefits are much greater than the costs and the seat yields a positive socio-economic return.

Figure 11 Socio-economic return results

COST-BENEFIT TOOL FOR VEHICLE SAFETY

Measure: Active headrest

Input

	lower	best estimate	upper
Costs per vehicle			
- Development costs	€ 15	€ 20	€ 25
- Manufacturing costs	€ 10	€ 15	€ 20
- Repair/replacement costs after a crash	€ 50	€ 78	€ 100
Crash risk (number of target crashes per vehicle per year)			
- before intervention	0,012	0,012	0,012
- after intervention	0,012	0,012	0,012
Road user characteristics			
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Vehicle life time (years)		15	
Discount rate		3,0%	

Results

	lower	best estimate	upper
Total costs	€ 32	€ 47	€ 60
Number of injuries prevented			
- Yearly	0,0005	0,0013	0,0026
- Total vehicle lifetime	0,008	0,020	0,039
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Benefits			
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- Medical costs reduction	€ 24	€ 59	€ 116
- Productivity gains	€ 117	€ 294	€ 577
- Total benefits	€ 388	€ 975	€ 1.913
Socio-economic return			
- Net present value	€ 329	€ 928	€ 1.880
- Benefit-cost ratio	6	21	59

3.2.7 Sensitivity analysis

The CBA tool allows conducting a sensitivity analysis by inserting upper and lower values for the inputs on cost, crash risk and injury probability, in addition to best estimates. This results in upper and lower limits of all outputs.[4] The upper BCR (balance) is calculated by dividing (subtracting) the upper value of the benefits by (from) the lower value of the costs, and vice versa. Ideally, the upper and lower values are based on confidence intervals.

Example

For the sake of illustration, Figure 11 includes (arbitrary chosen) upper and lower values of the costs involved in the improved seat for whiplash protection. In addition, upper and lower values of the injury probabilities are used (see Figure 7). The upper and lower probabilities, after the intervention, are based on a 12% and 36% risk reduction, based on Sandberg Eriksen et al. (Sandberg Eriksen, Hervik, Steen, Elvik, & Hagman, 2004). The other upper and lower values have been chosen arbitrarily as the study did not include confidence intervals for other variables. Due to the fact that upper and lower inputs are inserted for all inputs, the BCR shows a wide range (1.6 to 31.6). Alternatively, users may test the sensitivity of the results for a limited number of input variables, which logically results in more narrow ranges. This results in a wide range of the BCR (6 to 59). Alternatively, users may test the sensitivity of the results for a more limited number of input variables, which logically results in more narrow ranges.

[4] Note that lower (upper) injury reductions are calculated using the lower (upper) crash risks and injury probabilities before and after the intervention (instead the lower (upper) values before the intervention and the upper (lower) values after intervention, which could result in very broad ranges and negative injury reductions). The lower (upper) crash risks and injury probabilities do not necessarily result in the lowest (highest) injury reductions and monetary benefits. The lowest (highest) benefits are used in the lower (higher) estimate of the NPV and BCR, regardless of whether they are based on lower, best or upper estimates of crash risks and injury probabilities.

4 Input parameters and dedicated sources

This chapter provides an overview on input parameters for users of the VIRTUAL CBA tool. The content is based on M6.4 (Database with input parameters for CBA, including dedicated sources of data on injuries with low levels of reporting in official accident statistics). General information on different parameters is described and specific input parameters for VIRTUAL use cases are highlighted. This includes crash risk, cost of safety systems, injury probabilities and other parameters. Data availability, quality and other issues are also discussed. Recommendations are given to identify best possible input values.

This chapter recommends dedicated input parameters for the use of the VIRTUAL CBA tool. Most parameters are found in the main sheet of the CBA tool, see Figure 3 in Section 3.1. Furthermore, the parameters are not only described, but also predefined values as well as dedicated sources are presented. The following input parameters are described in this chapter:

- Crash risk (number of target crashes per vehicle per year) (Section 4.1)
  - Before intervention
  - Change after intervention
- Cost per vehicle (Section 4.2)
  - Development costs
  - Manufacturing costs
  - Repair/replacement costs
- Injury probabilities (Section 4.3)
- Number of target occupants per vehicle (Section 4.4.1)
- Average age casualties (Section 4.4.2)
- Life expectancy (Section 4.4.3)
- Vehicle lifetime (Section 4.4.4)
- Discount rate (Section 4.4.5)

In VIRTUAL WP3 and WP4, different use cases and, hence, different safety systems have been addressed aimed at enhancing safety for all occupants in cars and for VRUs. The use cases are shown in Table 4. Use cases that were addressed in CBAs are highlighted in bold. Due to limited resources and dependencies between WPs, not all use cases could be addressed for CBA within VIRTUAL. In this document, input parameters for the highlighted use cases are presented including some examples of safety systems. The structure is consistent in the following sections:

1. General information and potential data sources
2. VIRTUAL: Occupant protection
3. VIRTUAL: VRU protection

Table 4 VIRTUAL use cases identified for CBA, weherby only those in bold were adressed within the project. Use cases marked with * are included in this report.

Aim	Targeted crash type	Safety system
Occupant protection	Rear-end crashes (motorised vehicles)	**Improved seat design for reducing injury in rear-end crashes (WP3) ***
		Design principles to protect against injuries in new seated postures and seating positions in cars (e.g. rearward facing) (WP3)
		Improved design of child restraint systems to enhance efficiency (WP3)
VRU protection	Car – Pedestrian	**Active emergency braking to prevent cars from striking pedestrians and reduce impact speed (WP4) ***
	Car – Cyclist	**Active emergency braking to prevent cars from striking cyclists and reduce impact speed (WP4)**
	Tram – Pedestrian	**Design changes of tram fronts to reduce injury to pedestrians (WP4)**

Data availability, quality, and issues

Finding and choosing the correct input data is one of the main challenges in CBA of new safety systems. In two webinar sessions on 27th May 2021, suggested input values and/or data sources were mentioned as helpful, due to challenges in data availability and quality. For crash risk, underreporting is a main issue. Availability of information on the cost of safety systems is very limited. Deriving injury probabilities from HBM simulations demands specific knowledge. These issues and potential solutions or alternatives are discussed in each particular section. This chapter includes examples describing all steps needed to find and choose best possible input data for CBA.

4.1 Crash risk

4.1.1 General information and potential data sources

One of the necessary inputs for the tool is "*yearly crash risk before intervention*". The tool allows to input the best estimates of crash risk and their upper and lower values. In the tool, the crash risk has been defined as "*number of targeted crashes per vehicle per year*". Crash risk data should refer to the crashes the safety systems are aimed at, which means the crashes that are prevented by the safety system (in case of active safety systems) or the crashes for which the safety system (passive safety system) reduces injury severity (see Chapter 3). This section provides these risk estimates for the safety systems defined in VIRTUAL use-cases. Two risk estimates are provided, one in which the number of vehicles is used as the exposure measure, and another in which vehicle km travelled is used.[5]

4.1.1.1 Crash Risk

In the field of road safety, the concept of risk is used to quantify the level of safety relative to the amount of exposure. The terms risk and exposure should be defined within the context of the issue studied (Hakkert & Braimaister, 2002).
In this document, we distinguish between two definitions of risk. First, we calculate the risk as the probability of a targeted crash for one vehicle. In such calculations, the exposure measure is the total

[5] The current version of the tool does not allow to input risk estimates calculated with vehicle km travelled. However, we provide these estimates in this document, as a future version of the tool might have such an option.

number of targeted vehicles (i.e. it does not account for km driven by these vehicles). Additionally, we consider the risk as the probability of a targeted crash within an activity. We calculate such risk as the number of actual targeted crashes divided by the km driven by targeted vehicles. Both such calculations were chosen because they are easy to understand and interpret (Bjørnskau & Ingebrigtsen, 2015).

We calculated the crash risk for the following categories of crash consequences according to Community Road Accident Database (CARE) definitions. In case of trams, the categories are in accordance to the definitions from the police/public providers databases:

- All injury crashes
- Slight crashes
- Severe crashes
- Fatal crashes
- Fatal + severe crashes

Furthermore, we calculated upper and lower values at 95% confidence level for these risks. We have assumed that injuries and crashes are Poisson-distributed. The standard deviation is then equal to the square root of the number of crashes. A 95% confidence interval is obtained by multiplying the standard deviation by 1.96. The upper and lower 95% estimate of the number of crashes = number of crashes ± (1.96 * √the number of crashes). The confidence interval for risk is obtained after dividing the upper and lower value of the crashes by the exposure measure.

4.1.1.2 Crash data

In this document, to calculate the crash data, the actual (reported) number of crashes were used. The data on actual number of crashes are available from several sources. The most common sources are crash databases. WP4 distinguished three levels of databases - base, intermediate and in-depth (Klug, et al., 2020). For WP6 purposes, the base level databases are the most suitable. These databases are characterised by a large amount of data, which are not very detailed. On the European level, the most comprehensive base level database is the CARE (CARE, n.d.). CARE has a high level of disaggregation, (i.e. it contains detailed data on individual accidents as collected by the individual states). On a national level, every European country has its own base level crash database. Almost all of them are filled with police data. The data are usually publicly available to some extent; the level of availability differs between the countries.

When interpreting the crash data from these databases, we must be aware of differences in definition of injury levels and crash types between the countries. Furthermore, the police crash data suffer from well-known shortcomings, such as under-reporting, inaccurate injury levels, or missing data (Arun, Haque, Bhaskar, Washington, & Sayed, 2021). Combining police data with the data from medical care services can overcome some of these shortcomings. Generally, such data is only available in a limited number of countries and with limited information. The Swedish Traffic Accident Data Acquisition (STRADA) database is an exception which combines police data with the data from medical care services on a national level.

Using naturalistic driving data (NDS) might present an alternative to the official crash databases. Such data are collected in naturalistic driving studies in which drivers drive as they normally would, without specific instructions while a data acquisition system continuously monitor their driving. According to Grimberg et al. (Grimberg, Botzer, & Musicant, 2020), the larger NDS to date, in terms of data type and volume, were the Australian Naturalistic Driving Study (ANDS), Canada Naturalistic Driving Study (CNDS), the 100-Car study, the Strategic Highway Research Program 2 (SHRP 2), and the European Naturalistic Driving and Riding for Infrastructure & Vehicle safety and Environment (UDRIVE). From these, the US study SHRP 2 has been the largest and most comprehensive NDS. It collected data from 3,147 drivers during a 3-year data period, amounting to approximately 80 million vehicle kilometres

(50 million vehicle miles). Data collected included vehicle speed, acceleration, and braking; vehicle controls, when available; lane position; forward radar; and video views forward, to the rear, and on the driver's face (Victor, et al., 2015).

However, despite the large scale of these NDSs, the number of collected crashes is usually very low (Dozza, 2020). For example, in SHRP 2, the final dataset contained 46 rear-end crashes (Victor, et al., 2015). The UDRIVE study concluded, that almost hundred thousand hours of driving was not sufficient to find (enough) crashes to calculate actual risks (https://cordis.europa.eu/).

Naturalistic driving has gained increasing attention also in bicycle safety studies. These studies typically use instrumented bicycles, occasionally together with surveys and interviews (Werneke, Dozza, & Karlsson, 2015). They provide valuable data on behaviour, interaction, or conflict; however, their scale is limited in sample sizes, duration and geographically.

The shortcomings and lack of crash data can be overcome by using surrogates to crashes, such as safety-critical events (i.e. traffic conflicts). This assumes that there is a relation between the severity of the events and their frequency (Laureshyn, Svensson, & Hydén, 2010). For example, data from the accelerometer, speedometer and radar, enable searching for rear-end conflicts, the prevalence of which can provide a valid estimate of rear-end crashes (Tarko, 2020). It is also possible to model the risk, combining the data on crashes with conflicts, as done in SHRP2 (Victor, et al., 2015). In addition to NDS, conflicts can be identified in observational conflict studies, in driving simulator experiments or in microscopic simulations. However, all these methods have their limitations, such as being site-specific or lacking a validation of many conflict types (Arun, Haque, Bhaskar, Washington, & Sayed, 2021).

To conclude, the data from NDS studies have a potential to deliver the most precise estimates of crash risk, especially for motorised vehicles. The main reasons are high reliability and accuracy of data collected in real traffic. On the other hand, the number of crashes collected in existing NDS is low. Furthermore, the largest NDS were conducted overseas and a transferability of their results into European conditions is questionable. Instead of crashes, traffic conflicts could be used. However, such an approach is not feasible within WP6.
Thus, in WP6 we calculated the risk using crashes collected by the police (or public transport providers for tram crashes). This approach provides enough accuracy for demonstrative purposes of the CBA tool. We aim at gathering the crash data from a sample of European countries (the availability of data determines the selection of countries). To obtain the crash data, we primarily rely on the CARE database, due to wanting to be consistent with WP3 and 4. To obtain data on crashes involving trams (which are not included in the CARE database), we have considered crash databases of public transport providers and police in cities where VIRTUAL partners have the opportunity to access such data. Table 5 shows the sample of countries used in our risk calculations for each targeted crash type.

Table 5 Crash data used within the VIRTUAL project to calculate crash risks in selected countries

Country	Crash type			
	Rear-end	Car - Pedestrian	Car - Cyclist	Tram – Pedestrian*
Austria		x	x	x
Belgium		x	x	
Croatia		x	x	
Czech rep.		x	x	x
Denmark	x	x	x	
Finland	x			
France		x	x	
Germany	x	x	x	x
Hungary	x			
Italy	x			
Latvia	x	x	x	
Norway	x	x	x	
Poland	x	x	x	
Portugal		x	x	
Slovenia		x	x	
Spain	x			
Sweden		x	x	x
Switzerland		x	x	x

**for tram-pedestrian crashes, there are no data on national levels, but from selected cities from countries marked with x*

4.1.1.3 Exposure

The exposure measures how frequently people are exposed to situations or events that could lead to crashes. Elvik defined exposure as "the occurrence of any event in traffic, limited in space and time, that represents a potential for a crash to occur by bringing road users close to each other in time and/or space or by requiring the road user to act to avoid leaving the roadway." (Elvik, 2015). He identified three main types of exposure:

- Activity based (e.g. km driven or number of entering vehicles).
- Event based (e.g. potential conflicts, give-way situations, road user encounters).
- Behavioural based (e.g. pedestrian crossing behaviour),

Another type of exposure is population based, such as the number of vehicles or inhabitants. Population based measures do not capture actual participation in traffic (activity) and therefore only provide very rough estimates of risks. On the other hand, population data are most easily available from publicly open databases/sources.
There has been an on-going discussion about what measures of exposure should be used in risk calculations. Each has its own specifics, accuracy and consequences for interpreting the risk. According to Bjørnskau and Ingebrigtsen, exposure "must capture traffic participation, but at the same time it should not be too closely correlated with and thus a proxy for the accident" (Bjørnskau & Ingebrigtsen, 2015). Generally, the more aggregate the exposure, "the more intervening variables are introduced that cast shadows over the resulting risk calculations" (Hakkert & Braimaister, 2002).

In WP6 of the VIRTUAL project, we apply both an activity and a population-based exposure measure in risk calculations.

As the activity-based measure, we consider annual distance (vehicle km) travelled by vehicles relevant for the targeted crash type (i.e. cars and trams). To find the data on cars only, we applied the procedure described in the next section. Values of tram-km travelled are typically available from public transport operators on city level.

As the population-based measure, we consider number of vehicles in use. To obtain the data on car numbers we used the reports from the European Automobile Manufacturers Association (European Automobile Manufactures Association, 2018); (European Automobile Manufacturers Association, 2021) that provides data on annual numbers of vehicles of different types in every European country. We do not consider this measure for trams, because of lack of data on the number in use.

Estimate of car kilometres travelled

The PIN reports published by ETSC (Adminaite-Fodor, Carson, & Jost, 2021) & (Adminaite, Jost, Stipdonk, & Ward, 2017) provide overviews on distances travelled by all motor vehicles in most European states, as an annual average from a period of several years. In order to estimate the distance travelled only by cars in each country, we multiplied the data for each country by the factor 0.8. We selected this factor based on the data published in the United Nation report (UNECE, 2015) that contains all motor vehicles, as well as car km travelled in 14 European states in year 2013. The average share of car km in all km travelled in these states was 82% (with 7% standard deviation).

Table 6 shows the estimates of average annual distance travelled by cars in the two most recent periods in European countries used in WP6 risk crash calculations. These periods were selected to cover the periods of available crash data. Some countries only have crash data available until 2016 or 2017, whereas others hold more recent crash data. For countries with data available until 2019 or earlier, exposure data for 2014-2016 were used. For other countries, exposure data for 2018-2020 were used. The table contains all countries used for the risk calculations, which correlates with countries already used in WP3 and WP4, based on the most recent available crash data. Additionally, only countries already used in WP3 and WP4 were considered.

Table 6 Estimates of average annual distances travelled by cars (based on the 11th and 15th PIN Report)

Country	Annual distance travelled by cars (in millions km)	Time period	Annual distance travelled by cars (in millions km)	Time period
Austria	62,785	2012-2014	66,715	2017-2019
Belgium	79,261	2013-2015	82,54	2017
Croatia	19,085	2014-2016	20,955	2018-2020
Czech rep.	40,563	2014-2016	44,324	2018-2020
Denmark	38,092	2013-2015	40,698	2018-2020
Finland	43,705	2013-2015	39,831	2018-2020
France	460,027	2013-2015	497,453	2017-2019
Germany	602,347	2014-2016	581,093	2018-2020
Hungary	n.a.		35,695	??
Italy	396,092	2014-2016	402,69	2018-2020
Latvia	10,051	2014-2016	11,386	2018-2020
Norway	35,518	2014-2016	36,049	2018-2020
Poland	172,053	2014-2016	193,171	2017-2018
Portugal	53,186	2014-2016	55,541	2018-2020
Slovenia	14,101	2013-2015	17,293	2017-2018
Spain	n.a.		184,462	??
Sweden	64,728	2014-2016	65,586	2018-2020
Switzerland	51,166	2014-2016	53,556	2018-2020

Number of cars

We obtained the data on the numbers of cars from the European Automobile Manufacturers Association reports (European Automobile Manufactures Association, 2018); (European Automobile Manufacturers Association, 2021), as they provide data on the annual number of vehicles of different types used in all European countries. Table 7 provides these annual data for the period 2012-2019. For the risk analysis, we applied an annual mean value for the period covering the targeted crash dataset. For example, the data on pedestrian-car crashes were available for the period 2012-2016, therefore in the risk calculations we applied the annual mean values of the number of cars in relevant countries obtained during the period 2012-2016.

Table 7 Annual number of cars in use (European Automobile Manufacturers Association (ACEA) reports 2018 and 2021)

Country	Number of cars in use 2012	2013	2014	2015	2016	2017	2018	2019
Austria	4,584,202	4,641,308	4,694,921	4,748,048	4,821,557	4,898,578	4,978,852	5,039,548
Belgium	5,392,909	5,439,295	5,511,080	5,587,415	5,669,766	5,735,280	5,782,684	5,813,771
Croatia	1,445,000	1,433,563	1,458,149	1,476,229	1,528,119	1,567,883	1,665,391	1,728,911
Czech rep.	4,698,800	4,787,849	4,893,562	5,158,516	5,368,660	5,592,738	5,802,520	5,989,538
Denmark	2,225,164	2,265,349	2,320,982	2,392,180	2,465,946	2,529,973	2,593,585	2,650,225
Finland	2,560,190	2,575,951	2,595,867	2,612,922	2,629,432	2,668,930	2,696,334	2,720,307
France	31,600,000	31,650,000	31,799,000	37,458,000	37,934,000	38,371,000	38,336,000	38,215,000
Germany	43,431,124	43,851,230	44,403,124	45,071,209	45,803,560	46,474,594	47,095,784	47,715,977
Hungary	2,978,745	3,035,764	3,101,752	3,192,132	3,308,495	3,467,861	3,638,374	3,809,670
Italy	37,078,274	36,962,934	37,080,753	37,351,233	37,876,138	38,520,321	39,018,170	39,545,232
Latvia	618	634,214	657,487	575,685	594,295	617,791	636,671	656,875
Norway	2,433,147	2,487,254	2,539,513	2,592,324	2,639,245	2,693,021	2,720,013	2,768,990
Poland	18,744,412	19,389,446	20,003,863	20,723,423	21,675,388	22,503,579	23,429,016	24,360,166
Portugal	4,497,000	4,480,000	4,496,000	4,538,000	4,600,000	4,800,000	5,015,000	5,205,000
Slovenia	1,080,001	1,085,347	1,096,920	1,116,006	1,143,218	1,192,358	1,220,814	1,245,012
Spain	22,247,528	22,024,538	22,029,512	22,793,348	23,320,290	23,942,022	24,520,287	25,008,216
Sweden	4,447,165	4,495,473	4,585,519	4,669,063	4,768,060	4,845,609	4,870,783	4,887,904
Switzerland	4,300,036	4,366,895	4,430,375	4,503,865	4,571,994	4,620,630	4,665,390	4,572,188

4.1.2 VIRTUAL Occupant protection in rear-end crashes

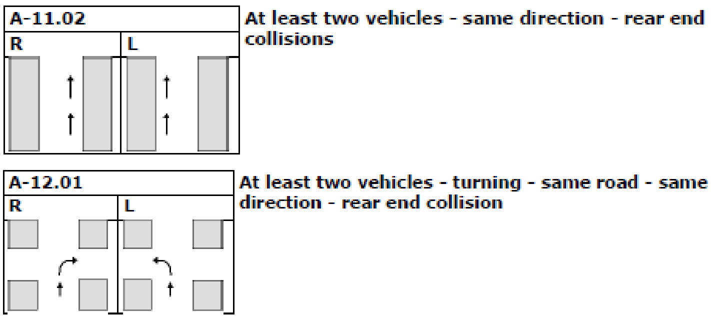
Rear-end crashes occur when a vehicle crashes into another one in front of it from behind. Most often, these crashes involve two vehicles – a leading (struck) and a following (striking) vehicle, while crashes involving three and more vehicles are less frequent. For example, in a US study by Khattak (Khattak, 2001), 87.6% of rear-end crashes were two-vehicle crashes. According to Khattak, the injury occurrence process in a two-vehicle rear-end crash is different from that in a three-vehicle rear-end crash. That study indicates that in a two-vehicle rear-end crash the leading driver is more likely to be injured, whereas in a three-vehicle crash it is the driver in the middle that is most at risk.
Rear-end crashes occur in all types of traffic environment, from residential areas to high-speed motorways, on both intersections and road sections. In the majority of rear-end crashes, the leading vehicle is stopped or moving very slowly (NHTSA, 2007). Regarding the vehicle type, most vehicles involved in rear-end crashes are cars. For example, in Norway, almost 80% of vehicles involved in rear-end crashes in the period 2016-2020 were cars (SSB, 2021).
Rear-end crashes are amongst the most frequently occurring type of crash. For example, in Norway, they were the second most frequent (15%) crash type during the period 2016-2020, after single vehicle accidents (SSB, 2021). The actual number of rear-end crashes is expected to be even higher. This is due to their lower reporting level – the consequences of many rear-end crashes are only minor and therefore not reported (Abdel-Aty & Abdelwahab, 2004).
In VIRTUAL, the safety systems targeting the consequences of rear-end crashes are improved seat design, new seated postures/seating positions and improved design of child restraint systems. These passive safety systems are relevant for struck car occupants.

Crash risk

As the safety systems tested in VIRTUAL are especially relevant for the leading car, it would be ideal to use the injury data specifically for leading cars involved in rear-end crashes.

Due to the unavailability of data on leading vehicles only, we did not distinguish between vehicle positions in the rear-end crashes. Thus, we used annual numbers of injuries of different severity levels in rear-end crashes involving at least one car as the most accurate numerator in the risk calculation. We obtained such data from the CARE database for the period 2015-2019. Figure 12 shows the considered crash types.

Figure 12 Considered rear-end crash types from the CARE database in which arrows represent vehicles



Regarding the exposure, the distance travelled by cars (in million km) and number of vehicles in use, represent the denominators in the risk calculations.

The crash rate for 1 million km = annual number of injuries in rear-end crashes involving at least one car / annual number of million car km travelled.

The crash rate for 1 vehicle = annual number of injuries in rear-end crashes involving at least one car / annual number of cars in use.

Table 8 provides the overview of the final dataset, Table 9 shows the calculated crash rates for each country, and Table 10 contains the overall risk estimates. The risk estimated were calculated by dividing the crashes in Table 9 by the exposures in Table 8.

Table 8 Available data for period 2015-2019: rear-end crashes

Country	Annual number of injuries			Mean annual cars km travelled (million)	Mean annual number. of cars in use
	Fatal	Severe	Slight		
Denmark	10	109	181	40,698	2,526,382
Finland	4	14	n.a.	39,831	2,665,585
Germany	189	4,921	63,255	581,093	46,432,225
Hungary	27	282	1,661	35,695	3,483,306
Italy	280	n.a.	n.a.	402,690	38,462,219
Latvia	3	14	265	11,386	616,263
Norway	3	30	765	36,049	2,682,719
Poland	143	769	4,080	193,171	22,538,314
Spain	57	464	19,985	184,462	23,916,833

Table 9 Crash risks for each country: rear-end crashes

Country	Crash risk per million km			Crash risk per car		
	Fatal	Severe	Slight	Fatal	Severe	Slight
Denmark	0.0002	0.0027	0.0045	$3.9582*10^{-6}$	$0.0431*10^{-3}$	$0.0716*10^{-3}$
Finland	0.0001	0.0004	n.a.	$1.5006*10^{-6}$	$0.0053*10^{-3}$	n.a.
Germany	0.0003	0.0085	0.1089	$4.0704*10^{-6}$	$0.1060*10^{-3}$	$1.3623*10^{-3}$
Hungary	0.0008	0.0079	0.0465	$7.7513*10^{-6}$	$0.0810*10^{-3}$	$0.4768*10^{-3}$
Italy	0.0007	n.a.	n.a.	$7.2799*10^{-6}$	n.a.	n.a.
Latvia	0.0003	0.0012	0.0233	$4.8681*10^{-6}$	$0.0227*10^{-3}$	$0.4300*10^{-3}$
Norway	0.0001	0.0008	0.0212	$1.1183*10^{-6}$	$0.0112*10^{-3}$	$0.2852*10^{-3}$
Poland	0.0007	0.0040	0.0211	$6.3448*10^{-6}$	$0.0341*10^{-3}$	$0.1810*10^{-3}$
Spain	0.0003	0.0025	0.1083	$2.3833*10^{-6}$	$0.0194*10^{-3}$	$0.8356*10^{-3}$

Table 10 Lower, best and upper estimates of overall crash risk: rear-end crahes

Crash risk for	Estimate for 1 million km			Estimate for 1 car		
	Lower	Best	Upper	Lower	Best	Upper
Fatal injury	0.0004	0.00047	0.0005	$4.6297*10^{-6}$	$4.9959*10^{-6}$	$5.3616*10^{-6}$
Severe injury	0.0057	0.0059	0.0060	$0.0614*10^{-3}$	$0.0630*10^{-3}$	$0.0645*10^{-3}$
Fatal + severe injury	0.0061	0.0063	0.0064	$0.0656*10^{-3}$	$0.0671*10^{-3}$	$0.0687*10^{-3}$
Slight injury	0.0828	0.0833	0.0838	$0.8760*10^{-3}$	$0.8825*10^{-3}$	$0.\ 8880*10^{-3}$
Any injury	0.0892	0.0898	0.0903	$0.9450*10^{-3}$	$0.9510*10^{-3}$	$0.9570*10^{-3}$

In the first example applying the CBA tool in rear end crashes, we used insurance data. The example can be found in Section 5.1.1.

4.1.3 VIRTUAL VRU protection

4.1.3.1 Car – Pedestrian crashes

In VIRTUAL, the safety system related to vehicle-pedestrian crashes is Active Emergency Braking System (AEBS). It aims at preventing cars from striking pedestrians and at reducing impact speed.

Cars are the most frequent vehicle type involved in motor vehicle-pedestrian crashes. For example, in Norway in the period 2016-2020, from all 1,723 pedestrian-motor vehicle crashes recorded by the police, 81,3% involved a car (SSB, 2021). Looking only at fatal crashes on the European scale, of over

50,000 pedestrians killed in the period 2010 to 2018 on EU roads, 68% were involved in a crash with a car (Adminaité-Fodor & Jost, 2020).

Crash risk

We considered a broader crash category - crashes between pedestrians and cars (in the period 2012 to 2016), as they were used in WP4. We distinguished between severity levels of injured pedestrians (i.e. slightly injured, seriously injured at 30 days and fatally injured at 30 days).

Regarding the exposure, the distance travelled by cars (in million km) and number of vehicles in use represent the denominators in the risk calculations.

The crash rate for 1 million km = annual number of injured pedestrians in crashes with cars / annual number of million car km travelled.

The crash rate for 1 vehicle = annual number of injured pedestrians in crashes with cars / annual number of cars in use

Table 11 provides the overview of the final dataset, Table 12 shows the calculated crash rates for the sample of countries, and Table 13 contains the overall risk estimates. The risk estimated were calculated by dividing the crashes in Table 12 by the exposures in Table 11.

Table 11 Available data for period 2012-2016: Car – Pedestrian crashes

Country	Annual number of pedestrian injuries			Mean annual cars km travelled (million)	Mean annual number of cars in use
	Fatal	Severe	Slight		
Austria	49	735	2,465	62,785	4,698,007
Belgium	61	396	2,939	79,261	5,520,093
Croatia	54	369	869	19,085	1,468,212
Czech rep.	98	431	1,908	40,563	4,981,477
Denmark	19	146	139	38,092	2,333,924
France	323	3,139	4,551	460,027	34,088,200
Germany	368	629	18,240	602,347	44,512,049
Latvia	41	79	577	10,051	615,936
Norway	10	71	305	35,518	2,538,297
Poland	790	2,599	4,586	172,053	20,107,306
Portugal	87	279	3,522	53,186	4,522,200
Slovenia	13	92	351	14,101	1,104,298
Sweden	30	196	828	64,728	4,593,056
Switzerland	35	469	1,223	51,166	4,434,633

Table 12 Crash risks for each country: Car – Pedestrian crashes

Country	Crash risk per million km			Crash risk per car		
	Fatal	Severe	Slight	Fatal	Severe	Slight
Austria	0.0008	0.0117	0.0393	$10.4300*10^{-6}$	$0.1564*10^{-3}$	$0.5247*10^{-3}$
Belgium	0.0008	0.0050	0.0371	$11.0505*10^{-6}$	$0.0717*10^{-3}$	$0.5324*10^{-3}$
Croatia	0.0028	0.0194	0.0455	$36.7794*10^{-6}$	$0.2513*10^{-3}$	$0.5919*10^{-3}$
Czech rep.	0.0024	0.0106	0.0470	$19.6729*10^{-6}$	$0.0865*10^{-3}$	$0.3830*10^{-3}$
Denmark	0.0005	0.0038	0.0037	$8.1408*10^{-6}$	$0.0626*10^{-3}$	$0.0596*10^{-3}$
France	0.0007	0.0068	0.0099	$9.4754*10^{-6}$	$0.0921*10^{-3}$	$0.1335*10^{-3}$
Germany	0.0006	0.0104	0.0303	$8.2674*10^{-6}$	$0.0141*10^{-3}$	$0.4098*10^{-3}$
Latvia	0.0041	0.0079	0.0574	$66.5654*10^{-6}$	$0.1283*10^{-3}$	$0.9368*10^{-3}$
Norway	0.0003	0.0020	0.0086	$3.9396*10^{-6}$	$0.0280*10^{-3}$	$0.1202*10^{-3}$
Poland	0.0046	0.0151	0.0267	$39.2892*10^{-6}$	$0.1293*10^{-3}$	$0.2281*10^{-3}$
Portugal	0.0016	0.0052	0.0662	$19.2384*10^{-6}$	$0.0617*10^{-3}$	$0.7788*10^{-3}$
Slovenia	0.0009	0.0065	0.0249	$11.7722*10^{-6}$	$0.0833*10^{-3}$	$0.3178*10^{-3}$
Sweden	0.0005	0.0030	0.0128	$6.5316*10^{-6}$	$0.0427*10^{-3}$	$0.1803*10^{-3}$
Switzerland	0.0007	0.0092	0.0239	$7.8924*10^{-6}$	$0.1058*10^{-3}$	$0.2758*10^{-3}$

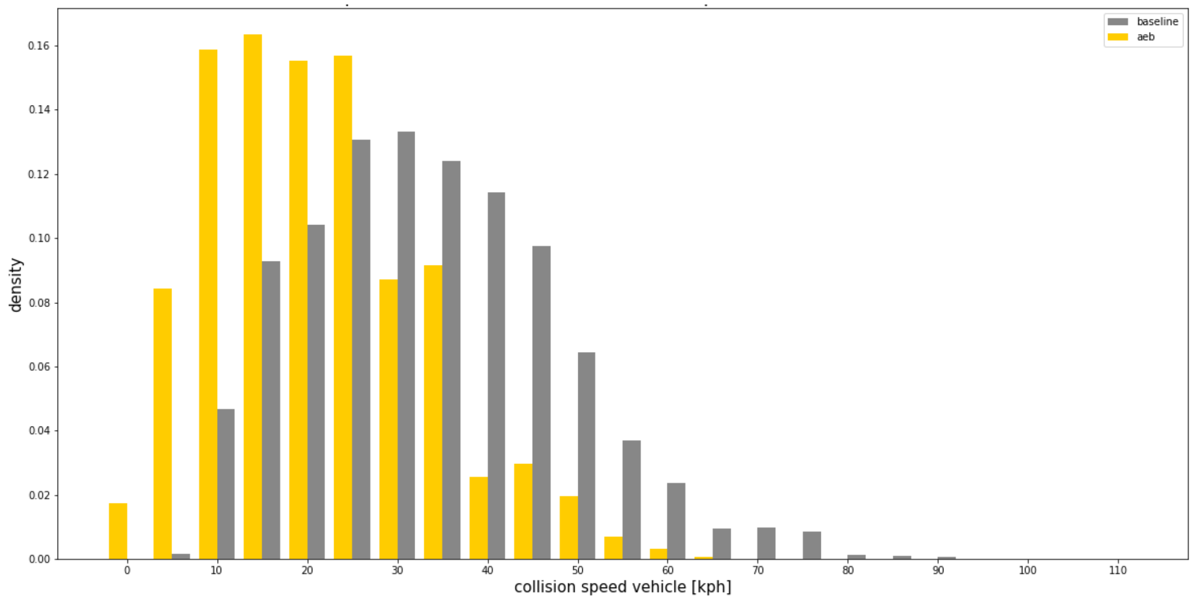
Table 13 Lower, best and upper estimates of overall crash risk: Car – Pedestrian crashes

Crash risk for	Estimate for 1 million km			Estimate for 1 car		
	Lower	Best	Upper	Lower	Best	Upper
Fatal injury	0.00111	0.00116	0.00121	$14.000*10^{-6}$	$14.5959*10^{-6}$	$15.200*10^{-6}$
Severe injury	0.00554	0.00565	0.00577	$0.0696*10^{-3}$	$0.0711*10^{-3}$	$0.0725*10^{-3}$
Fatal + severe injury	0.00669	0.00682	0.00694	$0.0841*10^{-3}$	$0.0857*10^{-3}$	$0.0872*10^{-3}$
Slight injury	0.02472	0.02496	0.02520	$0.3107*10^{-3}$	$0.3136*10^{-3}$	$0.3166*10^{-3}$
Any injury	0.03151	0.03177	0.03204	$0.3959*10^{-3}$	$0.3993*10^{-3}$	$0.4027*10^{-3}$

In Deliverable D4.1, a method of how accident occurrence can be estimated based on accident data from national statistics and in-depth investigations, was shown (Klug, et al., 2020). For this purpose, occurrence probabilities of individual configurations (e.g. injury severity and scenario type) were taken into account. The grey bars in the histogram in Figure 13 show the scaled and weighted speed distribution of all accident data.
After virtual introduction of an idealised AEBS in the VIRTUAL pre-crash simulation environment (Schachner, Sinz, Thomson, & Klug, 2020), a shift in collision speeds can be observed, indicated by the yellow bars. To make it more readable, the diagram does not include the avoided crashes, which amounted to 81.3%.

The testing protocol for performing such simulations for a specific AEBS is described in Deliverable D1.2 (Keller, et al., 2022).

Figure 13 Collision speed distribution of the vehicle for pedestrian collision scenarios



4.1.3.2 Car – Cyclist crashes

In VIRTUAL, the safety system related to vehicle-cyclist crashes is referred to as the Active Emergency Braking System (AEBS). It aims at preventing cars from striking cyclists and reducing impact speed.

Cars account for the most frequent vehicle type colliding with cyclists. Looking at fatal crashes on the European scale, of around 16,100 cyclists killed on EU roads in crashes with motor vehicles over the period 2010 to 2018, 64% were involved in a crash with a car (Adminaité-Fodor & Jost, 2020)

Any data, specifically regarding crashes involving a cyclist crossing in front of a straight driving car, is challenging to obtain. For example, data from Norway shows that 1,983 reported crashes between motorised vehicles and cyclists in the period 2016-2020 (including all severity levels), 714 (36%) were classified as "crossing direction of travel". However, to find out the direction of cars in these crashes would require detailed analyses of crash descriptions in the database.

Crash risk

We considered a broader crash category - crashes between cyclists and cars (in the period 2014 to 2016), as they were studied in WP4. Furthermore, we distinguished between severity levels of injured cyclists (i.e. slightly injured, seriously injured at 30 days and fatally injured at 30 days).

Regarding the exposure, the distance travelled by cars (in million km) and number of vehicles in use, represent the denominators in risk calculations.

> The crash rate for 1 million km = annual number of injured cyclists in crashes with cars / annual number of million car km travelled.
>
> The crash rate for 1 vehicle = annual number of injured cyclists in crashes with cars / annual number of cars in use

Table 14 provides the overview of the final dataset, Table 15 shows the calculated crash rates for the sample of countries, and Table 16 contains the overall risk estimates. The risk estimates were calculated by dividing the crashes in Table 15 by the exposures in Table 14.

Table 14 Available data for period 2014-2016: Car – Cyclist crashes

Country	**Annual number of injuries**			**Mean annual cars km travelled (million)**	**Mean annual number of cars in use**
	Fatal	**Severe**	**Slight**		
Austria	17	613	2,610	62,785	4,754,842
Belgium	35	495	5,341	79,261	5,589,420
Croatia	17	165	458	19,085	1,487,499
Czech rep.	30	177	1,331	40,563	5,140,246
Denmark	12	199	378	38,092	2,393,036
France	85	1,012	1,777	460,027	35,730,333
Germany	172	7,069	41,515	602,347	45,092,631
Latvia	7	17	268	10,051	609,156
Norway	2	46	296	35,518	2,590,361
Poland	187	986	2,129	172,053	20,800,891
Portugal	14	58	945	53,186	4,544,667
Slovenia	8	62	392	14,101	1,118,715
Sweden	10	149	1,114	64,728	4,674,214
Switzerland	11	393	1,542	51,166	4,502,078

Table 15 Crash risks for each country: Car – Cyclist crashes

Country	**Crash risk per million km**			**Crash risk per car**		
	Fatal	**Severe**	**Slight**	**Fatal**	**Severe**	**Slight**
Austria	0.0003	0.0098	0.0416	$3.5753*10^{-6}$	$0.1289*10^{-3}$	$0.5489*10^{-3}$
Belgium	0.0004	0.0062	0.0674	$6.2618*10^{-6}$	$0.0886*10^{-3}$	$0.9556*10^{-3}$
Croatia	0.0009	0.0086	0.0240	$11.4286*10^{-6}$	$0.1109*10^{-3}$	$0.3079*10^{-3}$
Czech rep.	0.0007	0.0044	0.0328	$5.8363*10^{-6}$	$0.0344*10^{-3}$	$0.2589*10^{-3}$
Denmark	0.0003	0.0052	0.0099	$5.0146*10^{-6}$	$0.0832*10^{-3}$	$0.1580*10^{-3}$
France	0.0002	0.0022	0.0039	$2.3789*10^{-6}$	$0.0283*10^{-3}$	$0.0497*10^{-3}$
Germany	0.0003	0.0117	0.0689	$3.8144*10^{-6}$	$0.1568*10^{-3}$	$0.9207*10^{-3}$
Latvia	0.0007	0.0017	0.0267	$11.4913*10^{-6}$	$0.0279*10^{-3}$	$0.4400*10^{-3}$
Norway	0.0001	0.0013	0.0083	$0.7721*10^{-6}$	$0.0178*10^{-3}$	$0.1143*10^{-3}$
Poland	0.0011	0.0057	0.0124	$8.9900*10^{-6}$	$0.0474*10^{-3}$	$0.1024*10^{-3}$
Portugal	0.0003	0.0011	0.0178	$3.0805*10^{-6}$	$0.0128*10^{-3}$	$0.2079*10^{-3}$
Slovenia	0.0006	0.0044	0.0278	$7.1511*10^{-6}$	$0.0554*10^{-3}$	$0.3504*10^{-3}$
Sweden	0.0002	0.0023	0.0172	$2.1394*10^{-6}$	$0.0319*10^{-3}$	$0.2383*10^{-3}$
Switzerland	0.0002	0.0077	0.0301	$2.4433*10^{-6}$	$0.0873*10^{-3}$	$0.3425*10^{-3}$

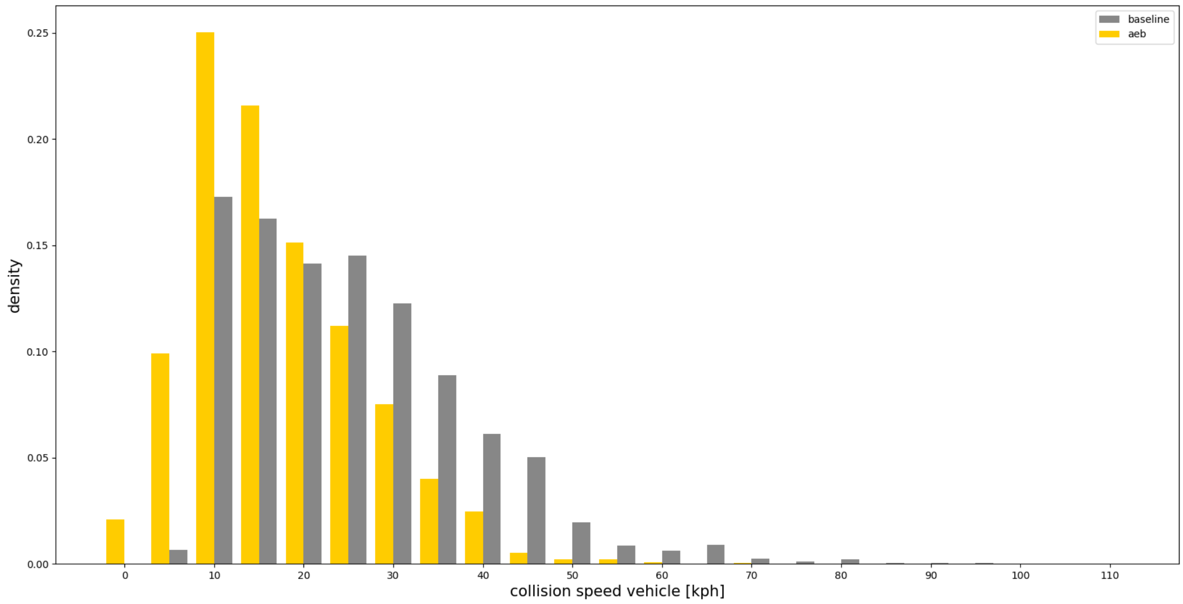
Table 16 Lower, Best and Upper estimates of overall crash risk: Car – Cyclist crashes

Crash risk for	**Estimate for 1 million km**			**Estimate for 1 car**		
	Lower	**Best**	**Upper**	**Lower**	**Best**	**Upper**
Fatal injury	0.00033	0.00036	0.00038	$4.0187*10^{-6}$	$4.3660*10^{-6}$	$4.7134*10^{-6}$
Severe injury	0.00660	0.00672	0.00684	$0.0808*10^{-3}$	$0.0823*10^{-3}$	$0.0838*10^{-3}$
Fatal + severe injury	0.00695	0.00707	0.00720	$0.0851*10^{-3}$	$0.0867*10^{-3}$	$0.0882*10^{-3}$
Slight injury	0.03501	0.03529	0.03557	$0.4288*10^{-3}$	$0.4323*10^{-3}$	$0.4357*10^{-3}$
Any injury	0.04205	0.04236	0.04267	$0.5151*10^{-3}$	$0.5189*10^{-3}$	$0.5227*10^{-3}$

The methods developed in Deliverable D4.1 have also been applied on vehicle to cyclist scenarios (Klug, et al., 2020). The histogram in Figure 14 shows the scaled and weighted speed distribution of the accident data (vehicle to cyclist). The introduction of an active safety system as described in D1.2 and the simulation of these baseline scenarios yields a shift (yellow) in accident configurations. Figure

14 shows the shift in collision speed through an idealised AEBS, for this specific vehicle (Schachner, Sinz, Thomson, & Klug, 2020). The simulations predicted that 53.8% of the crashes were avoided. As for the pedestrians, the testing protocol for performing such simulations for a specific AEBS is described in Deliverable D1.2 (Keller, et al., 2022).

Figure 14 Collision speed distribution of the vehicle for cyclist collision scenarios



4.1.3.3 Tram – Pedestrian crashes

In VIRTUAL, the safety systems related to tram-pedestrian crashes are "design changes of tram fronts to reduce injury to pedestrians". They aim at reducing the consequences for pedestrians involved in a crash with a tram. In WP4, the tram-pedestrian crash was identified as the targeted crash type. Trams are considered as a rail vehicle and only a few countries, such as Germany and Switzerland, include tram crashes in their road crash databases. In most countries, tram/public transport operators collect the data about tram crashes, typically on the city level. As the report TU1103 (COST - European Cooperation in Science and Technology, 2015) states, only one country (France) in Europe has a specific tram accident database at the national scale. On the European level no such database exists.

Due to the mass and shape of trams, tram-pedestrian crashes often have severe consequences for pedestrians. The most serious injuries arise when a pedestrian is run over by a tram. Among the factors affecting the occurrence of such crashes include the density of network, design of tram stops, type of trams (silence level, blind spots) or behaviour of pedestrians such as alcohol influence, inattention or risk behaviour (Sagberg & Sætermo, 1997); (Hedelin, Björnstig, & Brismar, 1996); (Hedelin, Bunketorp, & Björnstig, 2002); (Marti, Kupferschmid, Schwertner, & Weidmann, 2016); (Chevalier, Brizard, & Deillas, 2019), for example.

Crash risk

We are looking to establish the risk of a tram being involved in a crash with a pedestrian who then becomes injured (slightly, severely or fatally) in that crash. The number of crashes and their severities are affected by many risk factors specific to each city, such as the type of infrastructure separation, density of the network, type of trams involved, number of intersections, design of the stops and crossings, etc. Thus, to calculate the crash risks on each individual city level (and not on a country level) seems to be the most accurate approach. The selection of the cities was determined by the availability of data to WP4 and WP6 members (Lackner, et al., 2022).

For the risk calculation, we considered the number of injuries of different severity levels in crashes between a tram and a pedestrian as the most accurate numerators.

Regarding exposure, the distance travelled by tram (in million km) represents the obvious choice for denominator in the risk calculation.

Crash rate = annual number of injured pedestrians in tram-pedestrian crashes / annual million tram km travelled.

Table 17 provides an overview of the final dataset, while Table 18 and Table 19 contain the estimates of the risks.

Table 17 Data on km-travelled by trams and number of injuries in tram-pedestrian crashes for crash risk calculations

City (country)	Annual distance travelled by trams in (in millions km)	Annual number of injuries				Time period
		total	slight	severe	fatal	
Basel (CH)	6.29	6	4	2	0	2016-2019
Berlin (DE)	20.96	35.5	14.4	18.3	2.9	2010-2017
Bern (CH)	3.88	2	1.5	0.3	0.3	2016-2019
Brandenburg (DE)	0.75	0.5	0.4	0.1	0	2010-2017
Geneva (CHE)	5.29	4.5	2	1.8	0.8	2016-2019
Gothenburg+Mölndal (SW)	14.76	13.4	7.9	5.3	0.3	2014-2020
Graz (AT)	15.15	9.9	7.3	2.4	0.1	2014-2020
Innsbruck (AT)	10.4	2.3	1.7	0.6	0	2014-2020
Karlsruhe (DE)	8.6	23.1	13.6	8.5	1	2010-2017
Linz (AT)	7.8	6.9	4.9	1.7	0.3	2014-2020
Postdam (DE)	5.76	4.5	1.3	3.1	0.1	2010-2017
Prague (CZ)	56.04	68	55.6	8.4	4	2015-2019
Saarbrücken (DE)	1.9	7.9	2.9	4.6	0.4	2010-2017
Vienna (AT)	23.09	67.1	49.7	16.1	1.3	2014-2020
Zurich (CH)	17.39	23.5	16.3	6.5	0.8	2016-2019

Table 18 Crash risks for each city: Tram – Pedestrian crashes

City	Crash risk per million km		
	Fatal	Severe	Slight
Basel (CH)	0.000	0.318	0.636
Berlin (DE)	0.137	0.871	0.686
Bern (CH)	0.065	0.065	0.387
Brandenburg (DE)	0.000	0.167	0.501
Geneva (CHE)	0.142	0.331	0.378
Gothenburg+Mölndal (SW)	0.019	0.358	0.532
Graz (AT)	0.009	0.160	0.481
Innsbruck (AT)	0.000	0.055	0.165
Karlsruhe (DE)	0.116	0.988	1.584
Linz (AT)	0.037	0.220	0.623
Postdam (DE)	0.022	0.543	0.217
Prague (CZ)	0.071	0.150	0.992
Saarbrücken (DE)	0.197	2.434	1.513
Vienna (AT)	0.056	0.699	2.153
Zurich (CH)	0.043	0.374	0.934

Table 19 Overall crash risk estimates

Crash risk for	Estimate per 1 million km		
	Lower	Best	Upper
Fatal injury	0.049	0.063	0.077
Severe injury	0.411	0.448	0.486
Fatal + severe injury	0.473	0.513	0.553
Slight injury	0.879	0.934	0.988
Any injury	1.377	1.444	1.512

4.2 Costs per vehicle

4.2.1 General information and potential data sources

The three types of costs required for CBA are described in Sections 2.4 and 3.2.5. For a detailed explanation, please consider these sections.

For best case scenario, users of the tool, (e.g. manufacturers), have access to detailed information on costs for the assessed safety systems. This section is dedicated to users who do not know the cost of a particular system. The section guides the user through the most important aspects to find publicly available, but limited, information.

Most VIRTUAL industry partners and external industry partners were not allowed to share numbers due to strategic and confidentiality guidelines. Market prices are reasonable values representing developing and manufacturing costs. The costs involved in repairing/replacing a safety system can be estimated by using the market price for repair/replacement. If no information on the different costs is available, educated guesses or stipulated costs may be used. Another option is to conduct a break-even analysis. For the VIRTUAL CBA tool, price levels of 2018 should be used.

For users of the tool who do not know the costs involved in the assessed safety system, we suggest considering the report published by the European Commission: *"Benefit and feasibility of a range of new technologies and unregulated measures in the field of vehicle occupant safety and protection of vulnerable road users"* (European Commission, Directorate-General for Internal Market, Industry, Reed, Hynd, & Trees, 2015). This report offers a wide spectrum of available safety systems and their costs.

Please refer to Chapter 5 for how cost is used in the CBA tool.

4.2.2 VIRTUAL Occupant protection in rear-end crashes

In the VIRTUAL use case "Improved seat designs for reducing injury in rear crashes" (compare Table 4), the influence of active headrests was simulated using VIVA+ models. Active headrests can reduce the relative movement between head and torso in a rear-end crash. In Section 5.1, a detailed example is described including the costs involved in such a safety system. In this example, using values from 2004, we estimated the costs at €47. Recent market prices are notably higher, although it was not possible to obtain specific costs from manufacturers. A Toyota front seat headrest (without active headrest) is indicated at a retail price of $493.56 online (Toyota PartsPrime, n.d.). Estimated replacement cost for active headrests (Chrysler, Jeep, Dodge) fall between $600 - $800 (Kershaw Cook & Talley, 2018). These numbers have been derived from US websites and publications, respectively, and therefore costs are in dollar. The numbers could not be validated.

4.2.3 VIRTUAL VRU protection

4.2.3.1 Autonomous Emergency Braking System

The term Autonomous Emergency Braking System (AEBS) covers a wide range of different technologies and strategies to avoid crashes. Some only avoid rear-end crashes with other cars, whereas others can also detect pedestrians and cyclists. Some cars will only brake at the very last opportunity, whereas others decelerate more smoothly, like a driver would.

There are basically three main systems (Thatcham Research, n.d.):

- Lidar
- Radar

- Camera

The systems are also used in combination (e.g. radar and camera). The individual systems have different advantages and disadvantages and can be active at different travelling speeds. For example, a radar system works in bad weather conditions whereas an optical system can recognise and differentiate more objects. Therefore, a good strategy is to combine the systems. However, this has a relevant impact on the costs involved in the AEBS of a car. Users of the CBA tool need to know the exact field of use of their safety system.

In 2008, a TRL report stated estimated costs between €1,000 - €6,000 for developing and manufacturing AEBS (Grover, et al., 2008). Some years later, Edwards et al., stated that to be cost effective, AEBS recognising pedestrians should not exceed around €80 to €280 per car in Europe (Edwards, Nathanson, & Wisch, 2014). In 2015, a detailed report from the European Commission was published (European Commission, Directorate-General for Internal Market, Industry, Reed, Hynd, & Trees, 2015). The report differentiates between urban AEBS (typically lidar radars), inter urban AEBS (typically radar and camera), and pedestrian AEBS (typically camera and radar/lidar). The cost of a limited urban AEBS were stated to be as low as £200. Another urban AEBS, that also includes adaptive cruise control (ACC), park assist, and other functions, was stated to cost £2,320. AEBS rely on different components that are used for many different systems. Hence, it is very difficult to isolate costs for AEBS. This is also true for pedestrian AEBS. Pedestrian detection / night vision was mentioned with costs on average over €2,400. Consequently, for VIRTUAL use cases, summarised values from £2,000 -£3,000 for safety system packages including AEBS, are best estimates as input parameters for the CBA tool (European Commission, Directorate-General for Internal Market, Industry, Reed, Hynd, & Trees, 2015). We have found similar values in our review, which is summarised in Table 20. The third column "AEBS included in safety package" indicates if costs are explicitly for the AEBS or for a package where the AEBS is included.

Table 20 Costs of AEBS based on price of the safety system, which were published online (sources are found in the corresponding rows)

Make	Car model	AEBS included in safety package	Sensor	Car recogn.	Pedestrian and/or cyclist recognition	Speed in km/h	Costs in Euros	Source
Mercedes	C-Class	yes	Radar + Camera	yes	yes	over 50	€2,499	(ADAC, n.d.)
VW	Up	n.a.	Radar	n.a.	no	max. 30	€605	(Auto Motor und Sport, 2015)
Nissan	Qashqai	yes	Camera	yes	only moving objects	n.a.	€700	(Auto Motor und Sport, 2015)
Mini	n.a.	yes	n.a.	yes	yes	50	€990	(Auto Motor und Sport, 2015)
Subaru	Outback	n.a.	Camera	yes	n.a.	n.a.	€1,500	(Auto Motor und Sport, 2015)
Volvo	V60	n.a.	n.a.	yes	yes	n.a.	€2,150	(Auto Motor und Sport, 2015)
Mercedes	C-Class	yes	Radar + Camera	yes	yes	n.a.	€2,499	(Auto Motor und Sport, 2015)
Toyota	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	€500	(Allied Market Research, 2017)
Honda	n.a.	yes	n.a.	n.a.	n.a.	n.a.	€1,500-2,000	(Germain Honda, n.d.)

4.2.3.2 Improved tram front

For the use case in which the cost-benefit ratio of a softer tram front was assessed, costs had to be estimated based on the expertise of engineers. A cost estimate example for an improved tram front is shown in Table 21.

Table 21 Exemplary cost estimates for improved tram front – expert estimates from Siemens

Tram front (Mask)	Average cost per front (recurring)	Hardware Development (non-recurring)	Tooling (non-recurring)
Conventional	€4,000	€50,000	€30,000
Improved	€5,000	€130,000	€150,000

4.3 Injury probabilities

4.3.1 General information and potential data sources

Injury probabilities are a key input for the CBA tool, which are inserted into a separate sheet of the CBA tool (Figure 4 in Section 3.1). In VIRTUAL, we use injury probabilities derived from virtual testing with HBMs.

Injury probabilities are requested in percentages, categorised into male and female, before and after intervention as well as lower, best and upper estimate for each of the EUROCOST injury groups. A value of 0% means that no injury is likely to occur in the assessed injury group. In contrast, 100% means that an injury is likely to occur in every case. For the tool to perform a CBA, injury probabilities are not required for all 39 injury groups. For example, when assessing a whiplash protection system, Injury Group 8 "Whiplash injury/sprain of cervical spine" in the CBA tool is most relevant. Other groups irrelevant for assessing whiplash injuries, for example Injury Group 4 "Eye injury", are therefore not completed.

4.3.2 VIRTUAL use-case occupant protection in rear-end crashes

The example in Section 5.1 explains how injury probabilities for whiplash can be derived from HBM simulations. Injury probabilities are presented in this example.

4.3.3 VIRTUAL use-case VRU protection

A detailed description on data used to define the VRU virtual testing and crash scenarios can be found in Deliverable D4.1 (Klug, et al., 2020) as well as the upcoming Deliverable D4.2 (Leo, et al., 2022). Leo et al. (2021) published detailed injury analyses for pedestrians and cyclists (Leo, et al., 2021). To derive the injury probability for a specific vehicle with specific active and passive safety systems, instructions are given in Deliverable D1.2, where the virtual testing procedure for the holistic assessment of VRU safety developed in WP4, is described in detail (Keller, et al., 2022). In this procedure, precrash simulations are performed to estimate the capabilities of active safety systems to avoid crashes and mitigate crash severity. HBM simulations are then performed to predict the injury risk for different body regions within the remaining crash scenarios, and consequently analyse the effect of active and passive safety systems, combined for different scenarios comprising females and males.

In the following sections, results of the accident analysis performed in WP4 are summarised, which have been used as input for the assessment procedure and to determine the occurrence probabilities of certain conflict scenarios (Klug, et al., 2020).

An example of the application is given in Section 5.2, demonstrating how injury probabilities based on virtual testing are used to assess VRU protection by a generic AEBS.

Car – Pedestrian crashes

Looking into specific types of conflict situations for pedestrian crashes in STRADA and CARE, it has been possible to determine probabilities for certain conflict situations. The values shown in Table 22 have been obtained with the help of iterative proportional fitting (IPF), as described in detail in Deliverable D4.1 (Klug, et al., 2020), where the individual collision speed distributions per conflict scenario can be found as well. The values were used to link each of the 61,914 virtual testing scenarios with a baseline occurrence probability.

Table 22 Probability for specific types of pedestrian conflict situations as a result of IPF for STRADA and CARE data.

Conflict situation cluster	Conflict situation	STRADA Slight	STRADA Severe	STRADA Fatal	CARE Slight	CARE Severe	CARE Fatal
Car straight on, Pedestrian crosses	SCPPL	26.8	32.5	45	32.3	42.9	53.7
	SCPPR	44.1	31.7	20.9	53.2	41.9	24.9
	SCPPLSD	0.1	1.5	0.6	0.1	2.0	0.7
	SCPPLOD	0.0	0.0	0.0	0.0	0.0	0.0
	SCPPRSD	0.2	0.0	2.7	0.3	0.0	3.3
	SCPPROD	0.0	1.5	0.0	0.0	2.0	0.0
	Details unknown	0.0	0.0	0.0	0.0	0.0	0.0
Car turns, Pedestrian SD	LT/SD	3.7	7.7	0.0	3.9	4.2	0.0
	RT/SD	1.8	1.9	0.0	1.9	1.0	0.0
	LT/SDLD	0.0	0.0	0.0	0.0	0.0	0.0
	RT/SDRD	0.0	0.0	0.0	0.0	0.0	0.0
	Details unknown	0.0	0.0	0.0	0.0	0.0	0.0
Car turns, Pedestrian oncoming	LT/OD	4.7	0.0	3.8	3.6	0.0	1.7
	RT/OD	1.5	3.2	0.0	1.2	1.0	0.0
	LT/ODLD	0.0	3.2	3.8	0.0	1.0	1.7
	LT/ODRD	0.0	0.0	0.0	0.0	0.0	0.0
	RT/ODLD	0.0	0.0	0.0	0.0	0.0	0.0
	RT/ODRD	0.0	0.0	0.0	0.0	0.0	0.0
	Details unknown	0.0	0.0	0.0	0.0	0.0	0.0
Car and Pedestrian in longitudinal traffic	SD	3.6	5.0	10.3	2.4	2.2	9.4
	Oncoming	1.9	3.8	5.1	1.2	1.6	4.7
	Details unknown	0.0	0.0	0.0	0.0	0.0	0.0
Reversing	Reversing	11.7	8.0	7.7	0	0	0
TOTAL		100	100	100	100	100	100

For more details on the probability of different accident parameters for car – pedestrian crashes, please consider D4.1 (Klug, et al., 2020).

HBM simulation results are used for the CBA (Section 5.2) and will be presented in detail in Deliverable D4.2 (Leo, et al., 2022).

Car – Cyclist crashes

As for the pedestrians, the occurrence probabilities for the different conflict situation clusters can be found in Table 23, which enabled linking each of the 72,035 virtual testing scenarios considered in the holistic assessment with a baseline occurrence probability.

Table 23 Probability for specific types of cyclist conflict situations as a result of IPF for STRADA and CARE Data

Conflict situation cluster	Conflict situation	STRADA Slight	STRADA Severe	STRADA Fatal	CARE Slight	CARE Severe	CARE Fatal
Car straight on, Cyclist turns	SCPCROD	0.0	0.0	0.0	0.0	0.0	0.0
	SCPCRSD	0.5	1.7	0.0	0.2	6.6	0.0
	SCPCLOD	0.1	0.0	0.0	0.0	0.0	0.0
	SCPCLSD	0.8	1.7	0.0	0.2	6.6	0.0
	Details unknown	1.6	1.7	0.0	0.5	6.6	0.0
Car turns, Cyclist oncoming	LT/OD	5.8	4.0	0.0	6.0	0.0	0.0
	RT/OD	4.5	4.0	0.0	4.7	0.0	0.0
	Details unknown	0.0	4.0	0.0	0.0	0.0	0.0
Car turns, Cyclist SD	LT/SD	1.5	0.0	0.0	1.9	0.0	0.0
	RT/SD	6.9	6.3	0.0	8.3	6.6	36.6
	Details unknown	0.0	0.0	0.0	0.0	0.0	0.0
Car turns, Cyclist turns	LT/ODLD	0.0	0.0	0.0	0.0	0.0	0.0
	LT/ODRD	0.0	0.0	0.0	0.0	0.0	0.0
	LT/SDLD	0.0	0.0	0.0	0.0	0.0	0.0
	LT/SDRD	0.0	0.0	0.0	0.0	0.0	0.0
	RT/ODLD	0.0	0.0	0.0	0.0	0.0	0.0
	RT/ODRD	0.0	0.0	0.0	0.0	0.0	0.0
	RT/SDLD	1.1	0.0	0.0	0.0	0.0	0.0
	RT/SDRD	0.0	0.0	0.0	0.0	0.0	0.0
	Details unknown	0.0	0.0	0.0	0.0	0.0	0.0
Car turns, Cyclist crosses	LT/RD	1.3	0.0	0.0	0.8	0.0	0.0
	LT/LD	0.8	0.0	0.0	0.5	0.0	0.0
	RT/RD	5.7	0.0	0.0	3.6	0.0	0.0
	RT/LD	5.1	15.4	0.0	3.2	6.6	0.0
	Details unknown	0.0	0.0	0.0	0.0	0.0	0.0
Car straight on, Cyclist crosses	SCPCR	37.4	33.4	50.0	42.2	39.7	27.8
	SCPCL	19.2	18.4	50.0	21.7	21.8	27.8
	Details unknown	0.4	0.0	0.0	0.5	0.0	0.0
Car and Cyclist in longitudinal traffic	Oncoming	1.0	3.5	0.0	0.9	2.6	4.1
	SD	5.4	3.5	0.0	4.6	2.6	3.7
	Details unknown	0.0	0.0	0.0	0.0	0.0	0.0
Door	Door	0.9	2.1	0.0	0.2	0.2	0.0
TOTAL		100	100	100	100	100	100

For more details on the probability of different accident parameters for car – cyclist crashes, please consider Deliverable D4.1 (Klug, et al., 2020).

The HBM simulations performed to determine the injury risk before and after intervention for cyclists involved in car crashes, will be presented in Deliverable D4.2 (Leo, et al., 2022).

Tram – Pedestrian crashes
Injury probabilities and occurrence probabilities of certain scenarios for pedestrians hit by a tram were evaluated based on different European datasets and published as a joint effort between WP4 and WP6 (Lackner, et al., 2022). Also, in order to achieve a more comparable dataset than comparing simulations with field data, when assessing design changes of tram fronts to reduce injury to pedestrians, it is recommended to perform simulations with and without intervention using the VIVA+ models. With regard to the field data, however, it would be useful to check plausibility of the applied method. An improved tram front induces different injury probabilities for VRUs. The results of this use case will be presented in Deliverable 4.2. The CBA of improved tram fronts is planned to be part of a scientific publication.

4.4 Other data

4.4.1 Number of target occupants per vehicle

General information and potential data sources
The number of target occupants represents the number of occupants that experience a change by the intervention. Some systems are aimed at preventing injuries for one occupant (e.g. a passenger airbag), while other systems are aimed at more than one occupant (e.g. emergency braking systems).

VIRTUAL Occupant protection in rear-end crashes
The average number of occupants per car is required in order to assess the benefits of an occupant protection system in a rear-end crash.

VIRTUAL VRU protection
In the following VIRTUAL use cases, the numbers refer to the average number of VRUs involved in the crash scenarios.

- Car – Pedestrian
- Car – Cyclist
- Tram – Pedestrian

4.4.2 Average age of casualties

Average age of casualties affected by the safety system: To calculate the cost of an injury in terms of QALY, it is essential to establish the duration individuals will suffer the long term consequences of an injury. The costs are higher for an individual that is injured and suffers from permanent impairment at the age of 20 than for an individual who are injured at the age of 80. Therefore, the tool takes the average age of the targeted population into account. Users of the CBA tool should identify their target group and consider the average age accordingly.

For the general population, EUROSTAT (https://ec.europa.eu/eurostat/de/home) offers demographic parameters for countries in Europe (Eurostat, n.d.). Not mean, but median values for age of populations can be found. In return, not only median age of populations, but also separated medians of age for females and males can be found.

For the VIRTUAL use cases, values for the total population were used. The VIVA+ models are 50yo (John J. , Klug, Kranjec, Svenning, & Iraeus, 2022), which corresponds to the average age of adults in the European Union (European Commission, 2020).

This probably underestimates the age of the car occupants benefitting from the active headrest, since it does not affect children in child seats.

4.4.3 Life expectancy

Life expectancy of casualties affected by the safety system is, besides the average age of casualties, needed to calculate impact of long-term consequences of an injury. The two parameters allow to calculate the expected time lived with a disability (see Section 4.4.2).

Life expectancy of casualties affected by the safety system is, besides the average age of casualties, needed to calculate impact of long-term consequences of an injury. The two parameters allow calculating the expected time lived with a disability

Life expectancy values can be found in the EUROSTAT database (https://ec.europa.eu/eurostat/de/home), please follow the reference for direct access (Eurostat, n.d.). Values for the total population were used for the VIRTUAL use cases. However, these values probably overestimate the age of the car occupants benefitting from the active headrest, since it does not affect children in child seats.

4.4.4 Vehicle lifetime

The vehicle lifetime is the average number of years a vehicle equipped with the new safety system is used on the road. The vehicle lifetime strongly depends on the type of vehicle. The lifetime of cars is shorter than the lifetime of trams.

Cars

The vehicle lifetime of cars differs between countries within Europe. Therefore, it is preferable to use region specific numbers. For European average lifetime numbers, there are different databases available. Welt (2018) referred to ACEA with a vehicle lifetime of 11 years for 2016 (Welt, 2018). Statista published an average lifetime of 9.5 years for cars in Germany in 2019 (Statista, n.d.). Held et al. (2021) have highlighted the issue of neglecting import and export of cars to model the likelihood of a car reaching a certain lifespan (Held, Rosat, Georges, Pengg, & Boulouchos, 2021). In their model, they included imports and exports. They found average vehicle lifespans from 8.0 to 35.1 years. Western European countries show a mean lifespan of 18.1 years and Eastern European countries a lifespan of 28.4 years. For the example calculation within VIRTUAL, we used an average lifespan of 15 years (Wijnen, Bützer, Elvik, Pokorny, & Putra, 2022).

Trams

In contrast to cars, trams have an expected vehicle lifetime of around 40 to 50 years and operate for approximately 2.4 million km (VBZ, n.d.). Usually, tram operators provide information of the vehicle lifetime.

4.4.5 Discount rate

The discount rate is a percentual rate at which future costs and benefits are discounted, reflecting that the fact that costs and benefits have a lower weight if they occur later in the lifecycle of the vehicle. The European Commission recommends 3% for non-Cohesion countries and 5% for Cohesion countries (European Commission, 2014). Please consider Wijnen et al. (Wijnen, Elvik, & Bützer, 2020) for further clarification.

5 CBA use cases

This chapter introduces two examples of CBA of innovative safety systems based on VT.

5.1 VIRTUAL Occupant protection in rear-end crashes

In this section, an example of a virtually assessed active headrest aimed at reducing WADs is presented. The first example, showing all aspects of CBA of new safety systems using a virtual testing protocol, will be presented at the TRA conference 2022 (Wijnen, Bützer, Elvik, Pokorny, & Putra, 2022).

Whiplash injuries, also referred to as Whiplash Associated Disorders (WADs), is a frequently occurring group of injuries (Schmitt, Niederer, Cronin, Muser, & Walz, 2014). Annually, it is estimated that around 800,000 of European Union (EU) citizens suffer whiplash injuries (Linder, et al., 2013), and females show a higher risk of suffering WADs (Kullgren & Krafft, 2010). Although WAD injuries are not life-threatening, they can result in long-term health consequences as well as permanent disability (Kullgren A. , Krafft, Lie, & Tingvall, 2007); (Krafft M. , 1998).
Improved seat designs for reducing injury in rear crashes have been addressed in VIRTUAL. Whiplash protection systems have been identified as effective in real-world crashes (Kullgren, Stigson, & Krafft, 2013). Kullgren et al., identified energy absorbing seats, passive seats and reactive seats to reduce the risk for WAD for both males and females. Active headrests have shown a reduction of risk for males, but not for females. In VIRTUAL, we have been interested in finding out if active headrests can be effective for females, once the seat and the active headrest had been adapted and optimised for the anthropometry of a female.
Implementing active headrests is one method which can reduce the risk of WAD (compare Section 2.8). In case of a rear-end collision, the headrest is pushed forward in order to reduce the distance between the head and the headrest. This reduces the relative motion between the occupant’s head and the torso that occurs during a rear-end impact. The reduction in head and torso relative motion will subsequently reduce the relative motion between each vertebra in the neck. Previous studies have shown that reducing head to head-restraint distance could lead to a lower risk of sustaining whiplash injuries (Jakobsson, Isaksson-Hellman, & Lindman, 2008).

5.1.1 Injuries prevented

The injury risk reduction is calculated on the basis of crash risk and injury probability reduction. Data from the Swedish insurance company Folksam show that the annual risk (number of crashes per car) of a rear-end crash is 0.022 to 0.026. Similar values are seen in insurance data from AXA Switzerland. Risk values from police registrations are much lower (0.00075 in Sweden), which indicate a high underreporting rate. We use the upper value from the insurance data (0.026), because also the insurance data might suffer from some underreporting. Assuming that two cars are involved in a crash, the risk of a rear-end crash for the struck car is 0.013. The comparable value from AXA Switzerland is 0.015.

The probability of WAD occurring in these crashes for the situations with and without an active headrest was obtained from simulations with the VIVA+ HBMs, which have been developed within the VIRTUAL project (John J. , Klug, Kranjec, Svenning, & Iraeus, 2022). The average male and average female (VIVA+ 50F and 50M) were used and positioned in a Toyota Auris Finite Element (FE) seat model according to the procedure defined in Deliverable D1.2 (https://openvt.eu). The influence of head to head-restraint distance on WAD2+ risk, which implies complaint and musculoskeletal sign(s) including decreased range of motion and point tenderness (Spitzer, et al., 1995), was evaluated. Six different crash pulses, based on Folksam real-world accident data, were simulated. Each model (VIVA+ 50F and 50M) was run with the same crash pulse in two different head to head-restraint distances (120 mm and 95 mm) to simulate the impact of an active head restraint (Jakobsson, et al., 2022). Consequently, 24 simulations were performed. For each case, the Neck Injury Criterion (NIC), in m^2/s^2, was calculated based on the EuroNCAP protocol (EuroNCAP, 2020). As a next step, the probability of WAD2+ injury was calculated using a risk function developed by Ono et al. (Ono, et al., 2009). The risk function specifies the relation between the probability of WAD2+ injury and the maximum NIC value. Using the average curve, it was found that the likelihood of a WAD2+ injury was significantly lower for shorter head-to-head restraint distances in both female and male cases (Table 24), assuming a perfectly working active headrest. It was assumed that 60% of the mileage of a car is driven by men and 40% by women, as indicated by Dutch data on distance driven by gender (Statistics Netherlands, Statline database). Combined with the crash risk, this implies that the annual number of WAD2+ injuries per car decreases from 0.008 to 0.005. This also implies that 0.026 injuries per car are prevented during the vehicle lifetime, which is assumed to be 15 years, or one prevented injury per 26 cars.

Table 24 WAD2+ injury probability with and without headrest restraint (Jakobsson, et al., 2022)

	WAD2+ injury probability	
	Without active headrest restraint	**With active headrest restraint**
Male	61%	42%
Female	60%	39%
Average	60%	41%

5.1.2 QALY gains and monetary benefits

The injuries prevented by an active headrest are translated into QALYs using the method developed by Haagsma et al. (2012) as described in Chapter 3 (Haagsma, et al., 2012). A disability weight is only available for the acute phase of a WAD injury treated at the ED of a hospital, which is 0.073. This means that 0.073 QALYs are gained by preventing one injury. Estimates of the proportion of WAD that result in long-term health consequences range from 17% (Malm, Krafft, Kullgren, Ydenius, & Tingvall, 2008) to 50% (Teasell, Mehta, & Loh, 2020). We use 17% as a conservative estimate and assume that this proportion applies to both ED and HD casualties. In addition, we assume that the disability weight for long-term health consequences is (as a minimum) equal to the disability weight for the acute phase. The average age of the car occupant is assumed to be 50 years (the average in the EU as used as target age in the VIVA+ models (John J. , Klug, Kranjec, Svenning, & Iraeus, 2022)) and a life expectancy of 78 years for men and 83 years for women (source: EUROSTAT). Based on this information, the QALY gains per vehicle are estimated at 0.0014 annually or 0.022 during the vehicle lifetime. This translates into 1 QALY gained per 46 vehicles. The monetary value of the QALY gain is €1,200. In addition, the reduction of medical costs and the productivity gains are estimated at about €100 and €600, respectively. This results in a total monetary benefit estimate of €1,900 per car.

5.1.3 Costs

Cost information is available from a CBA of two whiplash prevention systems (Sandberg Eriksen, Hervik, Steen, Elvik, & Hagman, 2004), including an active headrest developed by SAAB. The cost of developing the whiplash prevention systems were estimated at about SEK 69 million in the period

1994-2003. This translates to €5.1 million in 2020 (using the harmonised price index for motor cars and purchasing power parities for individual consumption from Eurostat). The number of vehicles with the improved seat was estimated at 250,000, hence the development cost per vehicle is €20. The additional cost associated with manufacturing improved seats amounted to €15 per car (2020 prices). Although some active headrests are designed to be reused without additional costs, we have assumed that repair is needed after deployment. Repair costs are estimated at €78 per seat (2020 prices). Based on an annual crash risk of 0.013, a vehicle lifetime of 15 years and a 3% discount rate, the repair cost per vehicle (RC) are estimated at €11. The total cost per vehicle is, therefore, estimated to €47.

5.1.4 Socio-economic return

The calculations indicate that the benefits of active headrests are many times higher than the cost. The balance of benefits and costs (NPV) is €1,850 per car and the benefit is 40 times higher than the cost. This positive socio-economic return is explained by relatively rather low costs (€47 per car), while the impact of an active headrest on injury reduction and the related monetary benefits are significant.

5.2 VIRTUAL VRU protection

The safety system aimed at preventing car and pedestrian crashes, or reducing the severity of the resulting injuries, is the AEBS. The assessed AEBS is capable and aimed at preventing cars from striking pedestrians and at reducing impact speed, in particular crashes where a pedestrian (walking from various directions) enters the road in front of an approaching car (see Section 4.1.3.1).

5.2.1 Injuries prevented

The overall baseline crash risk (all injury severities) is estimated at $0.3993*10^{-3}$ (annual number of crashes per vehicle). See Table 13 in Section 4.1.3.1 or an overview of crash risk by crash severity (slight, serious and fatal) as well as lower and upper values. The crash risk reduction due to the introduction of an AEBS is estimated in our case at 81.3% based on the precrash simulations (see Section 4.1.3.1).

Injury probabilities for six injury types were estimated in WP4 based on HBM simulations with the VIVA+ models in collision with a generic vehicle front (see Section 4.3.3). The injury types include concussion, rib fracture, hip fracture, femur shaft fracture, tibia fracture and knee ligament rupture (interpreted as dislocation/sprain/strain of knee). For the lower extremity injuries, left and right body parts are distinguished. For severity concussion and rib fractures several categories are used; AIS1, AIS2 and AIS4+ and AIS1, AIS2 and AIS3+, respectively. Table 25 presents the results for the generic vehicle front. Upper and lower values were estimated for hip, femur and tibia fractures based on the confidence intervals of the self-developed risk curves. It shows that the introduced AEBS, and therefore changed impact conditions, reduced the probability of severe concussion (AIS4+) substantially. There is a shift to slight concussion observed for women as indicated by an increase in the probability of AIS1 concussion. The risk of rib fracture was reduced for all severities. For women there was a strong shift from severe to slight rib fractures. Furthermore, a substantial reduction in hip and femur shaft fractures was seen, although the range of values (lower versus upper) was extensive in some cases. Using the generic vehicle front, the probability of tibia fracture was relatively low and was further reduced by the AEBS, while the probability of knee ligament rupture decreased only slightly and seems higher in general compared to field data (Bützer, Lang, Schmitt, Zahnd, & Klug, 2020).

Table 25 Pedestrian injury probabilities before and after implementation of AEBS (%)

		Male						Female					
		Before			After			Before			After		
		lower	best	upper	lower	best	upper	lower	best	upper	lower	best	upper
Concussion	AIS1		*8,1*			*6,3*			*7,2*			*8,0*	
	AIS2		*24,4*			*15,6*			*22,7*			*18,4*	
	AIS4+		*38,9*			*14,2*			*46,1*			*15,4*	
Rib fracture	AIS1		*14,7*			*4,9*			*13,9*			*12,0*	
	AIS2		*8,6*			*5,3*			*8,3*			*2,7*	
	AIS3+		*27,4*			*14,4*			*17,5*			*0,5*	
Hip fracture	Left	7,0	*17,7*	31,0	2,0	*12,4*	27,0	16,0	*26,1*	38,0	8,0	*16,6*	28,0
	Right	10,0	*18,0*	29,0	2,0	*8,7*	19,0	37,0	*48,5*	58,0	7,0	*18,3*	31,0
Femur shaft fracture	Left	12,0	*18,4*	25,0	4,0	*9,8*	17,0	11,0	*17,1*	24,0	3,0	*6,8*	12,0
	Right	16,0	*26,4*	37,0	1,0	*3,2*	8,0	13,0	*23,0*	34,0	1,0	*3,3*	9,0
Tibia fracture	Left	2,0	*2,6*	5,0	0,0	*0,1*	1,0	0,0	*1,4*	5,0	0,0	*0,2*	2,0
	Right	2,0	*3,5*	7,0	0,0	*0,2*	2,0	1,0	*3,7*	10,0	0,0	*0,6*	3,0
Knee ligament rupture	Left		*98,2*			*94,2*			*92,1*			*83,1*	
	Right		*99,6*			*96,9*			*99,0*			*93,9*	

Combined with the crash risk reduction, the number of injuries prevented has been estimated at 0.014 per vehicle during the vehicle lifetime (assumed to be 15 years). This translates into 1 injury prevented per 47 cars equipped with AEBS.

The lower reduction in the number of injuries compared to the WAD use case is mainly caused by the much lower crash rate in the baseline, since VRU crashes are also often underreported. Furthermore, it must be taken into consideration that it is currently not possible to assess all potential injuries. The reduction in injury severity for the non-avoided cases affected by the AEB system (change in collision speed and impact location) depends on the vehicle structure and passive safety systems, and is in this case represented by a generic "averaged" vehicle structure, which does not correspond to a particular car. In the future such evaluation should be performed with FE vehicle models with serial cars with the latest protective measures addressing VRUs.

5.2.2 QALY gains and monetary benefits

To calculate QALY gains using the injury probabilities by AIS-level, the input data must be specified by AIS-level as well. This concerns data on disability weights, the proportion of casualties admitted to hospital and the proportion of lifelong consequences. Since the data presented by Haagsma et al. (2012) do not include AIS-categories, assumptions have been made based on the data for the total injury group from Haagsma et al., see in Table 26.

Table 26 Input data for QALY calculations. Source: Haagsma et al. 2012 ('All') and assumptions

		Disability weight acute phase		Proportion hospital admission	Proportion lifelong consequences	
		ED	HDR		ED	HDR
Concussion	AIS1	0,005	0,25	0%	0%	0%
	AIS2	0,01	0,5	0%	0%	0%
	AIS4+	0,03	2	30%	8%	50%
	All	0,015	0,1	7%	4%	21%
Rib fracture	AIS1	0,025	0,1	0%	-	-
	AIS2	0,075	0,225	30%	-	-
	AIS3+	0,15	0,5	90%	-	-
	All	0,075	0,225	61%	-	-

A life expectancy of 78 years for men and 83 years for women have been assumed, as well as an average age of pedestrians of 40 years (based on the CARE database, see (Klug, et al., 2020)), and a 50-50 distribution of male and female pedestrians (based on Swedish data, see (Leo, et al., 2021)). This results in a QALY gain of 0.027 per vehicle, or 1 QALY gain per 37 vehicles with AEBS.

The monetary benefits have been estimated at about €1,900 with an interval of €1,400 - €2,500. About 80% of the benefits (€1,500) are quality of life improvements (QALYs) and 20% (€400) concerns a reduction of medical costs and production loss.

With regard to prevented injuries, the lower benefits compared to the WAD use case are mainly caused by the much lower crash rate in the baseline, as VRU crashes are also often underreported. Furthermore, it must be taken into be consideration that it is currently not possible to assess all potential injuries, which is another reason why the benefit from avoiding more than 80% of the crashes is under-predicted.

5.2.3 Costs

As discussed in Section 4.2.3.1, the cost of AEBS depends on the type of AEBS. Therefore, an AEBS aimed at preventing crashes with pedestrians is likely to be in the range of €2,000 - €3,000. In the CBA we have used €2,500 as a best estimate, and €2,000 and €3,000 as lower and upper values. It should be noted that most systems do not only include AEBS but also, for example, adaptive cruise control and parking assistance. In principle the benefits of these functions should be included in the CBA as well, which is beyond the scope of this case study. Alternatively, the share of AEBS in the cost of the systems should also be estimated, which is not feasible. Therefore, the estimated cost should be considered an overestimation (or the benefits as an underestimation).

5.2.4 Socio-economic return

The calculations indicate that the benefits of installing AEBS are about equal to the costs. The benefits are estimated at €1,900 (€1,400 - €2,500) per vehicle while the costs are estimated at €2,500 (€2,000 - €3,000). This results in a negative NPV of €-600 with a range of €-1,600 - €500. The BCR is 0.8 with a range of 0.5 to 1.2. The CBA indicates that the socio-economic return is likely to be negative. However, as noted above, AEBS is often part of a system with more driver assistance systems, which are included in the (rough) cost estimate. As an example, most AEBS can efficiently avoid rear-end crashes with other vehicles. As seen in Section 5.1, avoiding WAD shows to have great benefits. The derived number could also be used for a break-even prediction, which would mean that if the cost for an AEBS is only below €1,900 (or €1,400 as a minimum), it would be assumed that benefits are higher than the cost for the specific scenario between cars and pedestrians. The socio-economic return is likely to be underestimated due to underreporting of VRU crashes as well as not assessing all potential injuries, as explained in Sections 5.2.1 and 5.2.2.

6 Discussion and Outlook

In VIRTUAL, not only the virtual testing toolchain with HBMs was successfully demonstrated, but also the use of simulation results to conduct CBA was shown. The examples presented in Chapter 5 are a first attempt to improve the standard CBA methodology in the context of road safety by using a detailed classification of injuries, applying HBMs to calculate safety benefits and calculating QALY gains. The methodology is embedded in a practical calculation tool for CBA of vehicle safety systems aimed at supporting stakeholders, such as the vehicle industry, road safety policy makers and NGOs, to conduct CBAs and to support decision making. Due to the complexity, we expect some stakeholders will require assistance in applying the CBA tool.

The CBA uses several standardised inputs, such as data needed for calculating QALYs and monetary valuations. However, in two webinar sessions with road safety professionals on 27th May 2021, it became clear that using the CBA tool and obtaining input data, particularly crash risk and cost of safety systems, can be challenging. Crash risk data may not be available in sufficient detail and data on cost is publicly available only for a limited number of safety systems, (e.g. through European studies on costs and benefits of vehicle safety systems). The automotive industry may be reluctant to provide such information for competitive reasons. To address the challenge of finding the correct input parameters, hence we have summarised our best estimates including explanations, to help users find the most suitable input values.
In case cost information is not available, the break-even costs can be calculated, which is the maximum cost that would equalise the benefits and costs. Experts could judge whether the real costs are likely to be lower than the break-even costs, which indicates whether or not the safety system is cost-beneficial.

The examples in Chapter 5 illustrate the feasibility of using the results of HBMs, in particular injury probabilities, as input for CBA in order to calculate safety benefits. Using HBMs enables studying systems which are not currently on the market or where insufficient field data exists. Hence, benefits can be studied under well-defined boundary conditions and injuries analysed in a more detailed and biofidelic way than with ATDs. However, simulations with HBMs can only be performed by skilled engineers or researchers. Furthermore, the number of trustworthy injury risk curves is still limited, especially when it comes to low severity injuries. Therefore, the feasibility of using HBMs depends on availability of risk functions.

Concerning the assessment of the safety benefits, the current version of the method and calculation tool concentrates on probability reduction of specific injuries within a specified injury severity category (e.g. WAD2+ in the case study in Section 5.1). The case study on AEBS illustrates the feasibility and added value of using different severity categories. However, input data required for calculating QALY gains, for example, disability weights, is not readily available. Collecting such data is recommended for further research.

The tool concentrates on the costs and benefits per vehicle. Assessments of vehicle fleets could be an interesting extension of the tool. This will allow, for example, assessing the costs and benefits of regulations on mandatory implementation of a safety systems in new cars, taking into account the current and expected future penetration rate. Additionally, the current version of the tool does not allow inputting risk estimates calculated with vehicle km travelled. It might be useful to include this feature in future versions of the tool.

Within the last few months of the project, the methodology will be applied to VIRTUAL use cases between cars and cyclists, but also between trams and pedestrians. In future, the CBA tool could be used to assess the costs and benefits of safety for public transport passengers, such as on buses or tramways. Moreover, the tool can also be used to assess further vehicle safety systems, or in connection with autonomous driving.

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