Inventory of assessed infrastructure risk factors and measures

Deliverable 5.4

SafetyCube

Inventory of assessed infrastructure risk factors and measures

Work package 5, Deliverable 5.4

Please refer to this report as follows:
Usami, D.S., Papadimitriou, E., Ziakopoulos, A., Quigley, C., Katrakazas, C., Durso C. (Eds) (2017), Inventory of assessed infrastructure risk factors and measures, Deliverable 5.4 of the H2020 project SafetyCube.

Grant agreement No 633485 - SafetyCube - H2020-MG-2014-2015/ H2020-MG-2014_TwoStages

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Project Start date: 01/05/2015

Duration: 36 months

Organisation name of lead contractor for this deliverable:
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Due date of deliverable:	**31/12/2017**	**Submission date:**	**31/12/2017**

Project co-funded by the by the Horizon 2020 Framework Programme of the European Union
Version: Final
Dissemination Level: PU Public

Co-funded by the Horizon 2020
Framework Programme of the European Union

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Executive summary

Safety CaUsation, Benefits and Efficiency (SafetyCube) is a European Commission supported Horizon 2020 project with the objective of developing an innovative **Road Safety Decision Support System (DSS)**. The DSS will enable policy-makers and stakeholders to select and implement the most appropriate strategies, measures, and cost-effective approaches to reduce casualties of all road user types and all severities. The three thematic pillars of SafetyCube, which have been tackled in parallel, are "Road Users", "Infrastructure" and "Vehicles".

This deliverable summarizes the results of the research work undertaken in Work Package (WP) 5 to develop the **"Inventory of road infrastructure safety measures"**, feeding the SafetyCube DSS (https://www.roadsafety-dss.eu/). The report describes the underlying methodology, the road infrastructure measures and related risk factors addressed in the inventory, the type of information the DSS user will find in the inventory related to research studies and their "synopses" (summary of results). Furthermore, it demonstrates the incorporation of developed contents into the Road Safety DSS and points out the specific challenges which make the research on infrastructure related risks and measures distinct from the thematic pillars "road users" and "vehicles".

The SafetyCube project had identified a **core group of stakeholders** from within government, industry, research, and consumer organisations covering the three road safety pillars of a Safe Systems Approach: vehicle, infrastructure, road user. Their needs and perceived "hot topics" were considered to ensure the relevance of the DSS.

Starting with the creation of a comprehensive list of risk factors specific to the road infrastructure and traffic environment, on the basis of several key publications, relevant information was sought on their general description, the related risk mechanisms, and a rough assessment of the safety effects (high / low or range of values, if known). A hierarchical **taxonomy** was created, with infrastructure elements (e.g. road surface, road environment, alignment, cross-section, etc.) including several general risk factors (e.g. road surface deficiencies, poor visibility, etc.), and in several cases each general risk factor includes many specific risk factors (e.g. uneven surface, ice, snow, etc.). A similar procedure was adopted to create a taxonomy of infrastructure measures. All risks and measures were analysed for all relevant road types.

Taking these considerations into account, studies were selected on the basis of the specially developed **SafetyCube methodology**, and the reported effects as well as further information like the research design were filled into a "coding template". The **predefined coding template** was a valuable tool to collect information in a standardized way so that results are comparable. Effects per study are fed into a **back-end database** (which underlies the Road Safety DSS) together with the further study information. Once all studies were coded for a risk factor or a measure, a **synopsis** was created, synthesising the coded studies and outlining the main findings in the form of meta-analyses (where possible) or another type of comprehensive synthesis (e.g. vote-count analysis). Each synopsis consists of three sections: a 2-page summary (including abstract, overview of effects and analysis methods); a scientific overview (short literature synthesis, overview of studies, analysis methods and analysis of the effects) and finally supporting documents (e.g. details of literature search and comparison of available studies in detail, if relevant). All infrastructure risk factor/measure synopses are available through the DSS.

To provide a rough impression for the user at first glimpse, a four-staged **"colour code"** was assigned per topic (thus, per synopsis) to indicate the riskiness of a risk factor or the effectiveness of a measure. Furthermore, the synopses contain theoretical background on the risk factor/measure and are prepared in different sections with distinct levels of detail for an academic as well as a non-academic audience. These sections are readable independently.

All the created synopses, underwent a self-imposed **quality assurance procedure**. At this point, due to this task, some of the synopses are still under review or being revised. As soon as the quality procedure is complete, updated synopses will be introduced into the Road Safety DSS.

For selected measures, namely those with proved effectiveness, for which related information could be found in the literatire, an economic evaluation in terms of cost-benefit analysis and corresponding sensitivity analysis was conducted. Within the SafetyCube project, European crash costs were updated (to 2015) and factors to correct for inflation as well as purchasing power parity were provided and applied to the measures costs.

Overhall, the inventory includes more than **240** coded studies on infrastructure related risk factors and more than **260** studies on infrastructure related mesures. Ultimately, **39 synopses** were written for road infrastructure-related risk factors, **48 synopses** on road infrastructure measures and **19 CBA synopses**.

The following tables give an overview of the assessed risk factors and measures and the colour code assigned to each of the topics. A synthesis of the cost-benefit analysis results is also provided.

Infrastructure related risk factors

Red (Risky)	Yellow (Probably risky)	Grey (Unclear)	Green (Probably not risky)
! **Effect of Traffic Volume on safety**	! Congestion as a risk factor	? Risks associated with Traffic Composition (HGVs only)*	✓ Poor Visibility – Darkness (cars only)*
! **Risks associated with Traffic Composition (VRUs only)***	! Occurrence of Secondary crashes	? Risks associated with the distribution of traffic flow over arms at junctions	
! **Road Surface - Inadequate Friction**	! Alignment deficiencies - Absence of Transition curves	? Adverse weather – Rain (other road users only)*	
! **Poor Visibility – Darkness (pedestrians only)***	! Road functional class	? Adverse weather - Frost and snow	
! **Adverse weather – Rain (motor vehicles only)***	! Poor Visibility – Darkness (all and two-wheelers only)*	? Alignment deficiencies - Frequent curves	
! **Workzone length**	! Poor visibility – fog	? Alignment deficiencies - Densely spaced junctions	
! **Alignment deficiencies - Low Curve Radius**	! Adverse weather – Rain (all)*	? Interchange deficiencies - Ramp Length	
! **Cross-section deficiencies - Number of Lanes**	! Workzone duration	? Interchange deficiencies - Acceleration / deceleration lane length	
! **Shoulder and roadside deficiencies -Absence of paved shoulders**	! Alignment deficiencies - High grade	? Poor junction readability - Absence of road markings and crosswalks	
! **Shoulder and roadside deficiencies - Narrow Shoulders**	! Presence of Tunnels		
! **Interchange deficiencies – absence of access control**	! Cross-section deficiencies - Superelevation		
! **At-grade junction deficiencies - Risk of different junction types**	! Cross-section deficiencies - Narrow lanes		
! **At-grade junction deficiencies - Gradient**	! Undivided road		
! **Uncontrolled rail-road crossing**	! Cross-section deficiencies - Narrow median		
	! Roadside deficiencies - Risks associated with Safety Barriers and Obstacles		
	! Roadside deficiencies - Sight Obstructions (Landscape, Obstacles and Vegetation)		
	! At-grade junctions deficiencies - Number of conflict points		
	! At-grade junction deficiencies - Skewness / Junction angle		
	! At-grade junction deficiencies - Poor sight distance		
	! Poor junction readability - Uncontrolled junction		

*The risk factors which are underlined have more than one colour code, but for different road user types.

Infrastructure related measures

Green (clearly reducing risk)	Light green (probably reducing risk)	Grey (Unclear)
✓ **HGV traffic restrictions** ✓ **Speed limit reduction measures to increase road safety** ✓ **Dynamic speed display signs** ✓ **Installation of section control & speed cameras** ✓ **Installation of speed humps** ✓ **Implementation of 30-zones** ✓ **Installation of lighting & Improvement of existing lighting** ✓ **Workzones: Signage installation and improvement** ✓ **Implementation of rumble strips at centreline** ✓ **Installation of chevron signs** ✓ **Traffic sign installation; Traffic sign maintenance** ✓ **Convert at-grade junction to interchange** ✓ **Sight distance treatments** ✓ **Automatic barriers installation at rail-road crossings** ✓ **Dynamic speed limits** ✓ **Creation of by-pass roads**	✓ Road safety audits & inspections ✓ High risk sites treatment ✓ Implementation of narrowings ✓ School zones ✓ Installation of traffic calming schemes ✓ Road surface treatments ✓ Increase median width ✓ Change median type ✓ Shoulder implementation (shoulder type) ✓ Increase shoulder width ✓ Safety barriers installation; Change type of safety barriers ✓ Create clear-zone / remove obstacles & Increase width of clear-zone ✓ Implementation of edgeline rumble strips ✓ Variable message signs ✓ <u>Convert junction to roundabout</u> ✓ Channelisation ✓ Installation of rail-road crossing traffic sign ✓ Traffic signal installation ✓ 2+1 roads	? Implementation of woonerfs ? Installation of median ? Increase number of lanes ? Increase lane width ? Change shoulder type ? Installation of cycle lane and cycle path ? V2I schemes ? <u>Convert junction to roundabout (cyclists)</u> ? Improve skewness or junction angle ? Convert 4-leg junction to staggered junctions ? STOP / YIELD signs installation / replacement ? Road markings implementation ? Implementation of marked crosswalk ? Traffic signal reconfiguration

*The measures which are <u>underlined</u> have more than one colour code, but for different road user types.

Cost-effectiveness classification of measures based on CBA results

		Costs (per unit)	
		Low [Costs < 100.000 €/unit]	High [Costs ≥ 100.000 €/unit]
Effectiveness	Low [BCR < 2.0]	Installation of chevron signs Traffic signal installation Installation of lighting & Improvement of existing lighting	Automatic barriers installation Installation of traffic calming schemes Installation of traffic calming schemes Dynamic speed limits Implementation of 30-zones
	High [BCR ≥ 2.0]	Road safety audits - Light measure case Winter maintenance Safety barriers installation High risk sites treatment Implementation of rumble strips at centreline	Road safety audits - Heavy measure case Traffic signal installation - highways Channelisation Convert junction to roundabout Section control Installation of speed humps

All created content was introduced into the DSS database and risk factors and measures were linked to each other within a Systems approach. Therefore, while this report documents only the infrastructure related risks/measures, the links have also been established cross-thematically to risks and measures related to road users and vehicles.

While the applied methodology and procedure were considered carefully, there are limitations to be considered. The already mentioned difficulty to quantify and / or separate infrastructure related risks and measures in terms of accident outcomes is one aspect. Exhaustiveness is another one. The aim was to cover as many infrastructure risk factors and measures as possible. However, it is not claimed to provide a comprehensive list of risks and measures. This is simply beyond the time resources at hand. However, in some cases, methodological difficulties were involved, and also the evidence base was not good enough. So, there are various reasons why one or the other risk factor/measure is missing in this document and the DSS, respectively. The goal is to not only maintain the DSS but to expand it to add what is not yet covered.

List of abbreviations

AADT	Annual average daily traffic
ADAS	Advanced Driver Assistance Systems
ASECAP	European Association of Operators of Toll Road Infrastructures
BCR	Benefit to Cost Ratio
BRRC	Belgian Road Research Center
CARE	Community database on Accidents on the Roads in Europe
CEDR	Conference of European Road Directors
CBA	Cost-benefit analysis
CI	Confidence interval
CMF	Crash modification factor
DSS	Decision Support System
EC	European Commission
E^3	Economic Efficiency Evaluation
ERSO	European Road Safety Observatory
ETSC	European Transport Safety Council
EURORAP	European Road Assessment Programme
FIA	Federation Internationale de l'Automobile
GIDAS	German In-Depth Accident Study
HGV	Heavy Goods Vehicle
IRTAD	Intenrational Road Traffic Accident Database
iRAP	International Road Assessment Programme
ISA	Intelligent Speed Adaptation
ITF	International Transport Forum
ITS	Intelligent Transport Systems
NPV	Net Present Value
OECD	Organisation for Economic Cooperation and Development
PPP	Purchase Power Parity
PR	Percentage Reduction
PTW	Powered Two Wheelers
QA	Quality Assurance
SPI	Safety Performance Indicator
TRB	Transportation Research Board
V2I	Vehicle to Infrastructure communication
VMS	Variable Message Signs
VRUs	Vulnerable Road Users
WP	Work Package

1 Introduction

This chapter describes the project and purpose of the deliverable. A short description of WP5 is also provided.

1.1 SAFETYCUBE

Safety CaUsation, Benefits and Efficiency (SafetyCube) is a European Commission supported Horizon 2020 project with the objective of **developing an innovative road safety Decision Support System (DSS)** that will enable policy-makers and stakeholders to select and implement the most appropriate strategies, measures and cost-effective approaches to reduce casualties of all road user types and all severities.
SafetyCube aims to:

1. develop new analysis methods for (a) Priority setting, (b) Evaluating the effectiveness of measures (c) Monitoring serious injuries and assessing their socio-economic costs (d) Cost-benefit analysis taking account of human and material costs
2. apply these methods to safety data to identify the key accident causation mechanisms, risk factors and the most cost-effective measures for fatally and seriously injured casualties
3. develop an operational framework to ensure the project facilities can be accessed and updated beyond the completion of SafetyCube
4. enhance the European Road Safety Observatory and work with road safety stakeholders to ensure the results of the project can be implemented as widely as possible

The core of the project is a **comprehensive analysis of accident risks and the effectiveness and cost-benefit of safety measures focusing on road users, infrastructure, vehicles and injuries framed within a systems approach** with road safety stakeholders at the national level, EU and beyond having involvement at all stages.

1.1.1 Work Package 5

The objective of the Work Package (WP) is the in-depth understanding of infrastructure related accident causation factors and the identification and evaluation of the most appropriate related measures. **This WP exploits a large amount of existing accident data (macroscopic and in-depth) and knowledge (e.g. existing studies) in order:**

i. to identify and rank risk factors related to the road infrastructure,
ii. to identify measures for addressing these risk factors,
iii. to assess the effects of measures.

WP5 thus contributes to all the objectives of SafetyCube, as listed in section 1.1 above, from a road infrastructure viewpoint. WP5 includes **four distinct and complementary Tasks**, as follows:
Task 5.1. Identification of infrastructure related risk factors
Task 5.2. Identification of safety effects of infrastructure related measures
Task 5.3. Evaluation of key infrastructure related road safety measures
Task 5.4. Inventory of road infrastructure safety measures

More specifically, the WP started with the creation of an exhaustive list of risk factors and road safety measures specific to the road infrastructure (**taxonomy**). For all these elements, a set of basic pieces of information were available within the existing literature, e.g. a general description, a rough assessment of the safety effects (high / low or range of values, if known) and the related costs (high / low, or unit costs if known), other effects (mobility, environmental etc.). The stakeholders' consultation was an additional source of basic information on the risk factors and measures.

This exhaustive list has been examined together with other project WPs, in order to make a selection of risk factors and measures that will be analysed and evaluated. For the selected risk factors and measures, the **methodologies and guidelines developed in WP3** (Martensen et al., 2017) are implemented and tested in the WP5 analyses. At the same time, care is taken that the conceptual framework of the analyses is consistent with the "systems" approach, that the combined effect of risks and measures related to more than one component of the system (user, infrastructure, vehicle) is taken into account. Eventually, the inventory includes research results on numerous risk factors and measures, together with an assessment of the quality of the data / study methods from which the results are obtained.

Overall, **a mixture of methods and data sources** have been utilised following the SafetyCube methodologies:

- existing and new data sources (macroscopic or in-depth) are used for carrying out original analyses.
- existing studies are examined for carrying out meta-analyses or other types of analysis allowing for comprehensive syntheses of results (e.g. vote-count analysis) to estimate the effects of risk factors and the efficiency of road safety measures.

Eventually, WP5 contributes to the **inventory of evaluated road safety risks and measures** related to road infrastructure, with results from accident risk factors analysis and measures cost-efficiency assessment, to be integrated in the DSS system.

1.2 PURPOSE OF THIS DELIVERABLE

This deliverable summarizes the results of the research work undertaken in Work Package (WP) 5 to develop the "Inventory of road infrastructure safety measures", feeding the SafetyCube Decision Support System (DSS). The report describes the underlined methodology, the road infrastructure measures and related risk factors addressed in the inventory, the type of information the DSS user will find in the inventory related to research studies and their "synopses" (summary of results).

This report is structured in six Chapters and three Annexes.

This **Chapter 1** provides background information about the SafetyCube project and the current Work Package.

Chapter 2 details the so called "hot topics" and the central SafetyCube methodology which has been applied for identifying and evaluating infrastructure related risk factors and measures.

Chapter 3 describes a taxonomy of the road infrastructure related risk factors addressed in the inventory, the type of information the DSS user will find in a coded study, the type of information the DSS user will find in a "synopsis". These synopses have been drafted on the basis of the codification of the studies and the meta-analyses that are at the core of the SafetyCube DSS.The chapter provides also an overview of the coded studies and synopses on road safety infrastructure risk factors that were acheived.

Similarly, **Chapter 4** considers infrastructure measures, presenting a taxonomy of measures and typical information available in the DSS. The chapter provides also an overview of the coded studies and synopses on road infrastructure measures and a summary of the main results from the effectiveness and efficiency analysis undertaken.

Chapter 5 discusses the key challenges that have been addressed within the analysis of infrastructure risks and measures and the main limitations of the analysis.

Subsequently, **Chapter 6** describes the steps taken for the quality assurance of the outputs of this research, and the technical work undertaken for their integration in the DSS, as well as a demonstration of the user experience in the form of DSS output examples.

Finally, **Chapter 7** summarises the main conclusions of this report.

Appendix A presents an abstract for each analysed infrastructure risk factor summarising the findings of the related synopsis.

Appendix B presents an abstract for each analysed infrastructure measure summarising the findings of the related synopsis.

Appendix C presents an abstract for each analysed infrastructure measure on the basis of the cost-benefit analysis synopses.

2 The SafetyCube Methodology for the Assessment of Risks and Measures

The identification and assessment of infrastructure related risk factors and measures was conducted on the basis of a broad stakeholders' consultation to identify user needs from the DSS and infrastructure "hot topics". Moreover, the work was in a standardized manner following the SafetyCube methodology developed to be applied to all the three thematic pillars (road user, infrastructure, vehicle) of the project.

2.1 IDENTIFICATION OF INFRASTRUCTURE "HOT TOPICS"

The **cooperation and interaction with a large group of stakeholders** was crucial for the smoothness and efficiency of each step of the project. The SafetyCube project had already identified a core group of stakeholders from within government, industry, research, and consumer organisations covering the three road safety pillars of a Safe Systems Approach: vehicle, infrastructure, road user. The future users of the ultimate product of the project (the DSS) include Public Authorities (local, regional, national, European and international level), Industry (Infrastructure, Vehicle, Insurance, Technology), Research Institutes, Non-Governmental Organisations, and Mass media.

2.1.1 Initial selection of "hot topics"

At every stage of the evolution of traffic and road safety science and relevant industries, there have been several areas that are of interest and attract particular attention by road safety researchers and stakeholders as critical areas for action and/or further research in recent scientific and policy documents. These have therefore been given particular emphasis and priority in the SafetyCube analysis, through a detailed and iterative process that was followed for their determination which is presented in the following. Initially, a selection of indicative **"hot topics"** was made at the project proposal stage, on the basis of international experience. These concerned the following thematic areas:

- **Road safety management**: Road safety impact assessment, Road safety audits, Roads star rating (e.g. EuroRAP), etc.
- **Self-explaining and forgiving roads**: simpler and more readable road design standards, related traffic arrangements for Vulnerable Road Users (VRUs), etc.
- **ITS (Intelligent Transport Systems) applications**: Vehicle to Infrastructure communication (V2I), cooperative systems, etc.
- **Urban road safety measures**: interventions developed to reduce the number of VRUs casualties in urban settings, e.g. stop-advanced-zones for motorcycles, traffic calming measures, bicycle lanes etc.

2.1.2 Stakeholder consultations

In order to identify user needs and further prioritise risk factors and measures "hot topics", three workshops were carried out. The first two workshops regarded a more general scope, whereas the third one was dedicated to infrastructure issues. The **first workshop** on June 17th 2015 was carried out in Brussels in order to start a dialogue between the project participants and a number of key stakeholders for road safety in Europe. The workshop both introduced the audience to the SafetyCube project and also solicited input from the stakeholders. The stakeholders who attended the workshop cover a wide range of interests and knowledge.

An extensive list of "hot topics" was created on the basis of feedback from stakeholders, allowing enhancement of the SafetyCube initial lists. To achieve the goal of identifying "hot topics", two activities were undertaken: two breakout sessions and a "hot topic" collection. The collection of "hot topics" was an ongoing activity throughout the day. The outcome of the "hot topics" exercise covered a wide range of subjects. For instance, there is an interest for the sharing of road environment between bicyclists, e-bikes, the elderly, and other traffic, both in shared space 30 km/h zones, crossings, and roundabouts. In the category "Infrastructure", speed limits on highways in different countries and dynamic speed limits were deemed important topics as well as road lighting, self-explaining roads, and forgiving roads.

A **second workshop** was organised in October 2015 in Ljubljana, Slovenia. The first part of the workshop was a plenary session with around 150 participants from the Slovenian Road Safety Councils and IRTAD (International Road Traffic Accident Database) group representatives. The SafetyCube project was presented as well as the "hot topics" from the previous workshop, and all participants were asked to give their feedback on the "hot topics". Feedback was collected both in spoken and in written form. The second part of the workshop was a breakout session continuing with participants from the IRTAD group. Thereafter the participants were asked to add, comment and prioritise the "hot topics". This was presented on 6 posters showing the "hot topics" from the previous stakeholder consultation.

The third **workshop, which was dedicated to road infrastructure** was carried out in February 2016, in Brussels, where twelve road infrastructure stakeholders participated. The participants represented key road infrastructure stakeholders, including EC-INEA, EC-DG-MOVE, EURORAP, ASECAP, ETSC, POLIS network, FIA, BRRC and Belgian regional road authorities. The objectives of the workshop were the analysis of infrastructure stakeholder needs for the DSS, as well as ranking the infrastructure related "hot topics" in terms of their importance. More specifically, the complete list of "hot topics" identified through the previous consultations was examined and ranked in this workshop dedicated to infrastructure.

Finally, the **SafetyCube Midterm Workshop in Brussels** (September 2016) was dedicated to showcase the first tangible results of the project and to acquaint stakeholders with the architecture as well as the appearance and functionality of the future SafetyCube Decision Support System. In addition, the workshop presented an opportunity to query stakeholders again on their priorities in terms of infrastructure measures.

2.1.3 Finalisation and ranking of hot topics

On the basis of the above consultations, the list of hot topics was enhanced with additional topics, and eventually a ranking was made.

Both the four general areas and the specific topics within each area were ranked. The four main areas are ranked as follows:

1. **Urban road safety measures** and
2. **Self-explaining and forgiving roads** (which received equal ranks),
3. **Road safety management**,
4. **ITS applications**.

As mentioned in section 2.1.1, these four "hot topic" areas were initially considered to be critical areas on the basis of international experience, from the project Technical Annex (developed since the project proposal phase). As such, at first they were not directly linked to a specific taxonomy entry. However, as the coding of studies progressed and the synopses topics were being consolidated, these were linked to the hot topics. In other words, there was both an active pursuit to investigate whether the synopses fall under a "hot topic" area and an active pursuit to explore these areas.

The top ranked specific infrastructure topics as rated by the infrastructure stakeholders for each area are shown in **Table 1**. The SafetyCube analyses have taken this ranking into account and add special emphasis on the highest priority topics. It is noted that several of the "hot topics" relate both to infrastructure risks *and* measures and hence were to be located in both the SafetyCube taxonomies of risk and measures.

Table 1: Ranking of the "hot topics" by road infrastructure stakeholders.

1.Urban road safety (detailed ranking was not possible)	2. Self-explaining and forgiving roads	3. Road safety management	4. ITS application
1. Pedestrians / cyclists	1. Removing obstacles	1. Quality of measures implementation	1. ISA
2. Upgrade of Crossings	2. Introduce shoulder	2. Appropriate speed limits	2. Dynamic speed warning
3. New crossings	3. Alignment (horizontal / vertical)	3. Enforcement	3. ADAS and active safety with V2I
4. Junctions / roundabouts treatments for VRU	4.Sight distance	4. Availability of cost-effectiveness data	4. Implementation of VMS
5. Visibility	5. Traffic signs	5. Work zones	
	6. Raised crossings / intersections		

2.2 OVERVIEW OF THE SAFETYCUBE METHODOLOGIES

A standard methodology was developed within the methodology Work Package of the SafetyCube project (WP3). This included:

- *Literature search strategy* to support Systematic literature search and selection of relevant studies on identified key measures,
- '*Coding template*' to record key data and metadata from individual studies,
- *Guidelines* supporting the analysis of key risk factors and measures on the basis of coded studies and summarising the findings in 'Synopses',

- *SafetyCube Economic Efficiency Evaluation* (E^3) Calculator, for priority setting between different road safety measures.

These documents and the associated instructions and guidelines can be found in Martensen et al (2017).

2.2.1 Literature search and Study selection

Literature Search

For each of the identified risk factor and measure topics **a standardised literature search** was conducted in order to identify relevant studies to include in the Decision Support System (DSS) and to form a basis for a concluding summary (*synopsis*) and further analyses. A standardised procedure was developed and applied for each examined risk factor/measure in SafetyCube. It should be noted that the literature search process was started for each risk factor and measure in the taxonomy, however, in some cases insufficient literature was identified and some risks/measures could not be evaluated. The literature search, study coding and synopses creation for a particular risk factor was completed within the same SafetyCube partner organisation. The process was documented in a standard format to make the gradual reduction of relevant studies transparent. This documentation of each search is included in the corresponding supporting documents of the synopses.

The **main databases used** in WP5 are the following:

- Scopus
- TRID

for some risk factors/measures the following **additional databases** were used:

- Google Scholar
- Science Direct
- Taylor & Francis Online
- Springer Link

Prioritising studies to be coded

The aim was to find studies that provided an estimate of the risk of being in a crash due to the presence of the risk factor, or the effectiveness of a measure in reducing crash risk or crash frequency. Therefore, **studies considering crash data were designated the most important**. However, while the actual occurrence of crashes can be seen as the ultimate outcome measure for road safety, Safety Performance Indicators (SPI) have in recent years been taken into consideration to quantify the road safety level (Gitelman et al., 2014). SPIs include driving behaviour, like speed choice and lane positioning. These metrics give an indication of safe (or unsafe) driving behaviour. The SPI variables included for analysis are those for which there is some scientific evidence of an association with increased crash risk. For some risk factors / measures, studies considering SPIs are included in addition to those focusing directly on crashes.

Since the study design and the outcome variables are just basic criteria, for some risk factors / measures the literature search had the potential to yield an excessive number of related studies and therefore additional selection criteria were adopted. Furthermore, on major and well-studied infrastructure topics, meta-analyses were available and the results of these were identified and incorporated. While the aim was to include as many studies as possible for as many topics as possible, it was simply not feasible, given the scope and resources of the project, to examine all available studies for all topics and their variants. The general **criteria for prioritising studies to be selected for further analysis and eventual inclusion in the DSS** were based on the following guideline:

- Key meta-analyses (studies already included in the key meta-analysis were not coded again)
- Most recent studies
- High quality of studies
- Country origin: Europe before North America/Australasia before other countries
- Importance: number of citations
- Language: English
- Peer reviewed journals

According to the level of detail of the topic and the history of research in the field, the exact approach to prioritisation and number of studies that were eligible for 'coding' varied (see Chapters 3 & 4 for the number of studies included per topic).

A challenge within the task of identifying studies to be included in the inventory was **to distinguish between risk factors and countermeasures**. For example, studies dealing with the absence of a safety barrier may be designed to record e.g. crashes before and after the installation of a safety barrier. Although dealing with a risk factor, these studies describe effects resulting from the treatment of a risk factor/application of a remedial measure. This particularity is discussed in more detail in Chapter 5 of this report.

2.2.2 Study Coding

Within the aim of creating a database of crash risk estimates and measure effectiveness related to road infrastructure design and layout, **a SafetyCube template was developed** to capture relevant information from each study in a manner that this information could be uniformly reported and shared across topics within the overall SafetyCube project. Guidelines were also made available for the task of coding with detailed instructions on how to use the template. The coding template was designed to accommodate the variety and complexity of different study designs. At the same time its complexity required partners to learn how to use it.

For each study the following information was coded in the template and presented in the DSS:

- Road system element (Road User, Infrastructure, Vehicle) and level of taxonomy so that users of the DSS will be able to find information on topics they are interested in.
- Basic information of the study (title, author, year, source, origin, abstract
- Road user group examined
- Study design
- Measures of exposure to the risk factor / measure
- Measures of outcome (e.g. number of injury crashes)
- Type of effects (within SafetyCube this refers to the numerical and statistical details of a given study in a manner to quantify a particular association between exposure (either to a risk factor or a countermeasure) and a road safety outcome)
- Effects (including corresponding measures e.g. confidence intervals)
- Limitations
- Summary of the information relevant to SafetyCube (this may be different from the original study abstract).

For the full list of information provided per study see Martensen et al (2017). Completed coding files (one per study) were uploaded to the DSS relational database. This database, with the included synopses and CBAs represents the inventory of road safety risks and measures.

2.2.3 Synopses Creation

The DSS will provide information for all coded studies (see above) for various risk factors and measures. **The synthesis of these studies is made available in the form of a 'synopsis'** indicating the main findings for a particular topic derived from **meta-analyses or another type of comprehensive synthesis of the results** (e.g. vote-count analysis), according to the guidelines and templates available in Martensen et al. (2016).

Synopses were created for different levels of the infrastructure risks and measures taxonomy, thus, for different levels of detail, mainly dependent on the availability of studies for a certain topic. The synopses contain context information for each risk factor from literature that could not be coded (e.g. literature reviews or qualitative studies). However, not all the coded studies that will populate the DSS are included in the analysis of the synopsis. For some topics where it was possible to code only a few studies, these coded studies will be included in the DSS. However, there was not enough information to write a full synopsis. Moreover, in some cases, taxonomy topics were merged in order to reach critical mass in terms of sound evidence for a synopsis.

The synopses aim to facilitate different end users: decision-makers looking for global estimates vs. scientific users interested in result and methodological details. Therefore, they contain sections for different end user groups that can be read independently. The **structure of each risk factor or measure synopsis**, including the corresponding sub items (uniform for human, vehicle, and infrastructure related topics), is as follows (*note*. Slight differences occur between synopses due to the variability in information from the literature):

1. **Summary**
    i. Abstract
    ii. Overview of effects
    iii. Analysis methods
2. **Scientific overview**
    iv. Short synthesis of the literature
    v. Overview of the available studies
    vi. Description of the analysis methods
    vii. Analysis of the effects: meta-analysis, other type of comprehensive synthesis like vote-count table or review-type analysis
3. **Supporting documents**
    viii. Details of literature search
    ix. Comparison of available studies in detail (optional)

Infrastructure-related crash scenarios using in-depth and macroscopic crash data

To enrich the background information in the **risk factor** synopsis, **in-depth accident data** from the German In-Depth Accident Study (GIDAS) and overview data from the CARE CADaS database was analysed[1]. There, where these data sources describe the relationships between an infrastructure risk factor and crashes, the related data has been included in that specific synopsis. Risk factors that were dealt with in the databases include **type of road, section of road (straight, junction etc) and crash type**. In these cases a radarplot is included in the synopsis to present the findings. In should be noted that the CARE data presents a summary situation for all EU member states (or as many as report figures for a particular risk factor). In contrast the GIDAS data is for Germany only. This may not be representative of other EU countries. The crash data provided in synopses are intended to serve only as an indication of the situation for the risk factor.

[1] French in-depth data (LAB database) data were also provided and examined but eventually not used in the synopses, mostly due to low number of cases for the risk factors concerned.

In-depth accident database GIDAS
Crash scenario analysis conducted using cases from the German In-Depth Accident Study (GIDAS) database considers all accidents which were ready for analysis and which were collected in the years 2007 to 2015. In total, records from 14, 398 accidents which occurred in the regions of Hannover and Dresden were analysed. The GIDAS database details those accidents which occurred on a public road where at least one person was injured. The accidents are collected according to a statistical sampling process to ensure a high level of representativeness of the actual accident situation in the sample regions. The data collection is conducted using the "on the scene" approach where all factors which were present at a crash are recorded. This does not mean that the recorded factor was a contributory factor towards the crash. Note that, the risk factor is identified in relation to the involved party who was considered most at fault.

CARE Accident database
Crash scenario analysis conducted using cases from the CARE Database, considers all fatal accidents[2] recorded in year 2013. In total, records from 23 577 accidents which occurred in 28 European countries were analysed. CARE Database comprises detailed data on individual accidents as collected by the Member States. Data are recorded according to a Common Accident Data Set (CADaS) consisting of a minimum set of standardised data elements, which allows for comparable road accident data to be available in Europe.

Final Synopses

Ultimately the inventory includes 39 synopses on road infrastructure risk factors and 48 synopses on road infrastructure measures that have been considered for inclusion in the DSS. It must be noted that due to available studies and some contents of the synopses their titles were slightly adapted by the authors in certain cases. More details on the infrastructure risk factors and measures synopses available in the inventory are provided in chapters 3 and chapter 4.

Colour Code
To indicate the overall conclusion about the road safety risks or the effectiveness of a measure a colour code was assigned to each of the studied risk factors and measures (**Table 2**). The colour code is based on the results of the studies and previous described analyses. A short statement gives further information about the reasons for choosing this colour code. In the DSS the colour code and the link to the synopses is shown on the search results page (see chapter 6 for examples).

Table 2: Description of colour codes for risk factors and countermeasures (Martensen, 2017).

	Risk factor			Countermeasure
Red	Results consistently show an increased risk when exposed to the risk factor concerned.		Green	Results consistently show that the countermeasure reduces road safety risk.
Yellow	There is some indication that exposure to the risk factor increases risk, but results are not consistent.		Light green	There is some indication that the countermeasure reduces road safety risk, but results are not consistent.

[2] Data refer to those accidents where at least a person was fatally injured (death within 30 days of the road accident, confirmed suicide and natural death are not included).

Grey	No conclusion possible because of few studies with inconsistent results, or few studies with weak indicators, or an equal amount of studies with no (or opposite) effect.			
Green	Results consistently show that exposure to the presumed risk factor does not increase risk.		Red	Results consistently show that the countermeasure does NOT reduce road safety risk and may even an increase it.

2.2.4 The Economic Efficiency Evaluation tool

Within the SafetyCube-project an Economic Efficiency Evaluation (E^3) calculator has been developed. This tool is one in which information regarding the effectiveness of a certain road safety measure and its implementation costs are present. In addition, such a tool can determine the costs and benefits in monetary terms and allows for further analyses. An E^3 tool is currently incorporated in SafetyCube as a Microsoft Excel application. This section is a brief description of the tool. Further information can be found in Wijnen & Martensen (2016).

In order to use the tool, certain inputs and considerations should be taken into account. First of all, it is important to mention that the tool assumes that the road safety measures are evaluated in specific units of intervention, such as a vehicle equipped with a safety system or a specific infrastructure location. Furthermore, for the purposes of the E^3 tool it is important to define certain concepts including:

- **Crash Modification Factor** (**CMF**): A CMF consists of a multiplier applied to the crashes that occurred before the implementation of the measure. A CMF is used to estimate the number of crashes that will occur when the measure is implemented and is a measure of the expected effect.
- **Effectiveness** (**E**) or **percentage reduction** (**PR**) is defined by the formula E=PR=100*(1-CMF) and it represents the reduction of crashes after the measure is implemented.

The following **Figure 1** gives an overview of the E^3 tool.

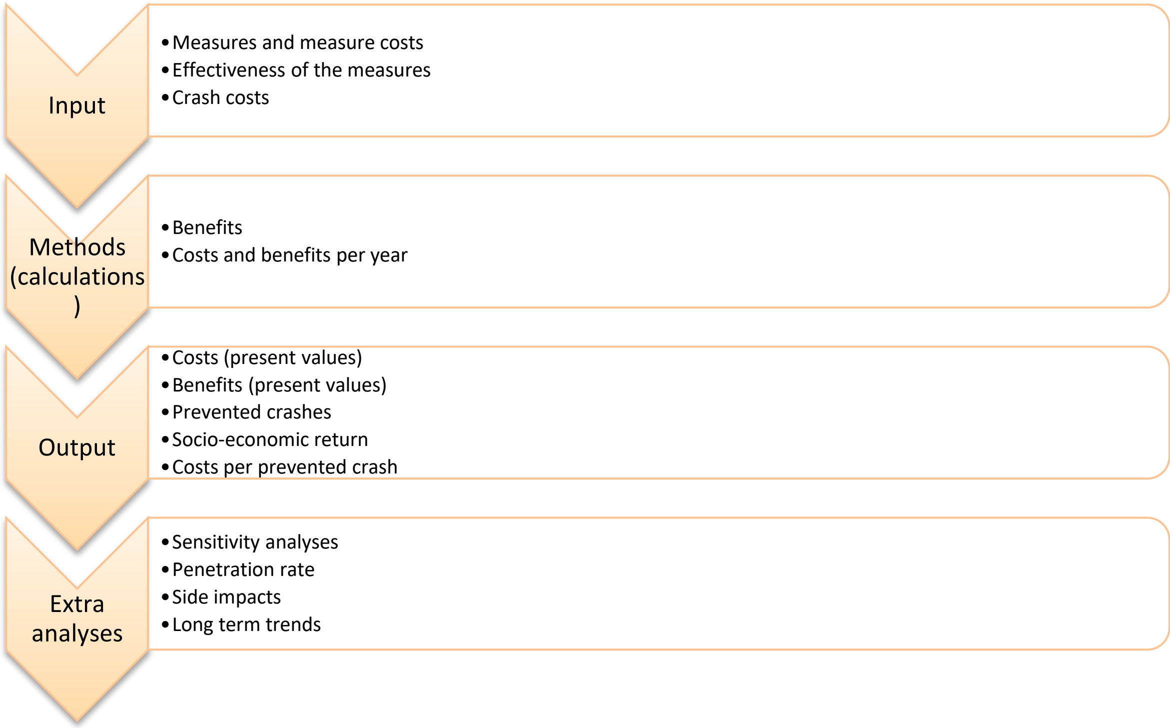

Figure 1 Overview of the SafetyCube E3 Tool

Inputs

First it is important to consider whether a specific road safety measure or intervention helps preventing crashes or reducing the outcomes of crashes. In the E^3 tool, all the measures that can prevent crashes are assessed as a reduction of crashes and it is recommended to take into account different levels of severity of crashes when estimating the effectiveness of the measures. That is due to the fact that the implementation of a certain measure can lead to different costs and benefits (and have different effects) depending on the level of severity.

Second, when including the costs of a road safety measure as an input of the E^3 tool, maintenance costs and implementation costs should be considered and introduced in the tool on a yearly basis. These costs differ per country. These costs have to be updated to 2015 since this is the year in which the costs of crashes (benefits), that are provided in the E 3 tool, are expressed.

Another important input for the tool is the target group, the number of crashes in which the safety measure is expected to have an impact. In the tool, the target group should be specified for all the levels of severity that have CMF data available. Moreover, the effectiveness (or percentage reduction) should be added for each severity level.

In the E^3 tool, a database with all the crashes and costs is available per country and for all European countries together, according to the level of severity. The user can select the relevant data for the country s/he wants to analyse from the database as an input for the analysis.

Method

First of all, the benefits, depending on the level of severity of the road crash, derived from the introduction of a measure, are calculated as follows.

$$Benefits = \sum_{s} TargetCrashes_s * Effectiveness_s * CrashCosts_s$$

Where, s= severity level.

The tool calculates the costs and benefits on a yearly basis considering by default a time period of 30 years (but different implementation periods may also be specified). First, the actual values of the implementation and maintenance costs are calculated. Then, a discount rate that can be chosen as an input is applied to obtain the present value of the costs as follows.

$$present\ value = \frac{actual\ value}{(1 + discount\ rate)^{year}}$$

The benefits represent the number of crashes avoided per year due to the implementation of the measure. The actual value of these benefits is calculated by multiplying the costs for each target group with its effectiveness.

Output

The output consists of the present values of the costs and benefits of implementing the measure over the selected time period (e.g. 30 years).
Net present value and benefit-cost ratio are also shown, calculated with the following formulas to estimate the socio-economic return of introducing the measures:

Net present value = Present value benefits – Present value costs
Benefit-cost ratio = Present value benefits / present value costs

Other analyses

Extra analyses might be included in the tool. For example, sensitivity analyses, penetration rate of the measures, side effects derived from the implementation of the measure and trends on a long term basis.

Analysis procedures

In order to implement the SafetyCube methodologies described above, the following steps were taken.

A selection procedure was followed for **topics meaningful candidates for a CBA**.

First, a literature review was performed for the candidate topics of the SafetyCube infrastructure measures taxonomy, in order to identify existing published CBAs, that could be used as a basis for SafetyCube CBAs. The studies found were analysed to identify usable data elements. The items of interest were:

- **Target group, unit of implementation and time horizon**: a specific case study was sought, clearly defining these elements, in combination with other relevant information; however, in most cases this was not possible, so the researcher had to define his/her own case study.

- **Measures costs**: costs associated with a specific case study (unit of implementation, target group etc.) were preferred, otherwise a value transfer from another source case study was performed.

- **Measures safety effects**: these could be available either through the previous WP5 work which summarised the safety effects of measures (by means of meta-analysis, or other comprehensive synopsis), or through a specific CBA in the literature.

In general, there were two options for conducting a CBA on the selected measures:

Generic CBA: this would be the preferred option when a meta-analysis with confidence intervals of the estimate of the measure was available, as such an estimate is considered highly reliable and transferable. However, in this case no "perfectly matching" measure cost and target group was available. Consequently, a generic unit of implementation and related target group was defined, and measure's cost information was sought from the available sources and value-transferred to the generic context, as required.

Adjustment of an existing CBA: if no meta-analysis was available giving a generic estimate of the measures safety effect, specific case-studies were sought from the literature, with particular emphasis on existing CBAs. The advantage of this case is the "matching" measures cost, implementation conditions and safety effect; which is however at the detriment of transferability of the estimates. The existing case-study was adjusted in two ways: first, with the improved SafetyCube crash costs estimates, and second, with the update of all figures and estimates to the reference year 2015.

More details on the adopted methodologies and analysis procedure are available in Daniels & Papadimitriou (2017).

3 Road infrastructure related risk factors

This chapter highlights which are the road infrastructure related risk factors addressed in the SafetyCube inventory, how the results are presented, summaries of the type of information the DSS user will find in a coded template, the types of information the DSS user will find in a synopsis and an overview of the results.

3.1 WHAT IS A RISK FACTOR?

Within the SafetyCube project **'risk factor' refers to any factor that contributes to the occurrence or the consequence of road accidents**. Risk factors can have a direct influence on the risk of an accident occurring, on the consequences of the accident (severity), or more indirectly by influencing a Safety Performance Indicator (SPI). All elements of the road system are potential crash risk factors. In this sense, the risks associated with road elements, the traffic environment, or other events occurring on the road network are also included. This report deals with risk factors that are related to the design and layout of the road infrastructure.

3.2 RISK FACTORS ADDRESSED

The first step in order to be able to identify and rank infrastructure related risk factors in terms of their impact on accident causation was the development of **a taxonomy**. The aim of creating a taxonomy is to identify the relevant topics covering all aspects of infrastructure and road environment risk factors, and structure them in a meaningful way (e.g. general topics such as alignment at junctions, specific topics such as gradient), **to serve as the back-bone of the analyses**.

In order to do so, existing studies on infrastructure related risk factors were thoroughly reviewed. This included several **key resources and publications** analysing or comparing infrastructure risk factors and measures, such as:

- **ERSO** web-text on infrastructure (http://ec.europa.eu/transport/road_safety/specialist/erso/pdf/safety_issues/road_safety_mesures/01-roads_en.pdf),
- **The Handbook of Safety Measures**,
- **CEDR** Report on 'Cost-Effective Infrastructure Investments',
- **ROSEBUD** Handbook,
- **SUPREME** Handbook,
- **Highway Safety Manual**,
- **OECD/ITF** report on 'Sharing Road Safety',
- **PRACT** research project (EU repository of infrastructure CMFs),
- **iRAP** toolkit and related publications,
- **SWOV** fact-sheets (http://www.swov.nl/UK/Research/factsheets.htm).

The initial list of risk factors was then examined on the basis of the methodological framework developed within the project and the underlying systems approach, in order to make the **final comprehensive selection and a meaningful classification** of risk factors that would be analysed, ranked and evaluated in terms of their impact on accident causation and severity. The WP5 partners' experience with infrastructure risk research also contributed to the adjustment and optimisation of the list. Eventually, **59 specific risk factors within 16 general risk factors, all within 10 infrastructure elements,** were identified. In particular, a hierarchical taxonomy was created, with infrastructure elements (i.e. general topics) including several general risk factors, and in several cases each general risk factor includes many specific risk factors (see Tables 3-10).

The **infrastructure types** covered in the SafetyCube taxonomy include:

- Freeway segments.
- Interchanges (including speed change lanes, ramp segments, crossroad ramp terminals).
- Rural road segments.
- Rural junctions (including rail-road crossings).
- Urban road segments.
- Urban junctions.

Several risk factors concern more than one type of infrastructure (e.g. road surface-related risk factors). The question whether to distinguish taxonomies per road type was extensively discussed at the beginning of the research, as it is one of the key dimensions of the analysis. Because road types are a horizontal aspect spanning many topics (which are applicable to different road types), we opted not to further distinguish risks and measures per road type in the taxonomy, but address each risk/measure for all relevant road types.

Tables 3 to 10 illustrate the entire taxonomy of risk factors utilised in WP5 of the SafetyCube project. Overall categories of infrastructure elements were considered first and then the specific risk factors were assigned to the respective element and general risk factor. **Risk factors indicated by stakeholders as 'hot topics' are highlighted in orange**. The 10 **infrastructure and traffic environment elements** that were included are as follows, while Tables 3-10 give an overview of the specific risk factors:

- Exposure.
- Road type.
- Road surface.
- Road environment.
- Presence of work zones.
- Alignment - Road segments.
- Cross-section - Road segments.
- Traffic control - Road segments.
- Alignment - Junctions.
- Traffic control - Junctions.

Table 3: Taxonomy of road infrastructure risks related to exposure.

Infrastructure element	General risk factor	Specific risk factor
Exposure	**Traffic flow**	Effect of traffic volume on road safety
		Congestion as a risk factor

		Occurrence of secondary crashes[3]
		Risks associated with varying traffic composition (share of pedestrians, cyclists, PTW, HGV)
		Risks associated with the distribution of flow over arms at junctions

Table 4: Taxonomy of road infrastructure risks related to road type, road surface and road environment.

Infrastructure element	General risk factor	Specific risk factor
Road type	**Road functional class**	Road functional class[4]
Road surface	**Road surface deficiencies**	Inadequate friction
		Uneven surface
		Ice, snow
		Oil, leaves, etc.
Road environment	**Poor visibility**	Darkness
		Fog
	Adverse weather	Rain
		Snow & frost
		Wind

Table 5: Taxonomy of road infrastructure risks related to work zones.

Infrastructure element	General risk factor	Specific risk factor
Work zones	**Presence of work zones** *hot topic*	work zone length
		work zone duration
		Insufficient signage

Table 6: Taxonomy of road infrastructure risks related to alignment - road segments.

Infrastructure element	General risk factor	Specific risk factor
Alignment - Road segments	**Horizontal / vertical alignment deficiencies**	Alignment deficiencies - Low curve radius
		Alignment deficiencies - Absence of transition curves

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[3] Although secondary crashes are in fact an outcome related to the risk factor "primary crash or other traffic incident", the term "occurence of secondary crashes" is used in the taxonomy for a clearer depiction of the examined consequences of the risk factor.

[4] This topic aims to address the risks associated with different road types, and in particular with the fact that not having the appropriate functional class for the type of road connection can potentially increase the likelihood of crashes occurring.

	hot topic	Alignment deficiencies - Frequent curves
		Alignment deficiencies - Densely spaced junctions
		Poor sight distance - horizontal curves
		Alignment deficiencies - High grade
		Alignment deficiencies - Vertical curve radius
		Presence of Tunnel
		Poor sight distance - vertical curves

Table 7: Taxonomy of road infrastructure risks related to cross-section - road segments

Infrastructure element	General risk factor	Specific risk factor
Cross-section - Road segments	**Super elevation / cross-slopes**	Cross section deficiencies - Superelevation at curve
		Cross section deficiencies - Cross-slope
	Lanes / ramps deficiencies	Cross section deficiencies - Number of lanes
		Cross section deficiencies - Narrow lane
	Median / barrier deficiencies (risk of crash with oncoming traffic)	Undivided road
		Cross section deficiencies - Narrow median
	Shoulder and roadside deficiencies	Absence of shoulder *hot topic*
		Narrow shoulder *hot topic*
		roadside deficiencies - Absence of guardrails or crash cushions
		roadside deficiencies - Absence of clear-zone
		roadside deficiencies - Roadside obstacles (per type of obstacle e.g. trees) *hot topic*
		roadside deficiencies - Risks associated with Safety Barriers *hot topic*

Table 8: Taxonomy of road infrastructure risks related to traffic control - road segments.

Infrastructure element	General risk factor	Specific risk factor
Traffic control - Road segments	**Poor road readability** *hot topic*	Absence of traffic signs
		Misleading or unreadable traffic signs
		Absence of road markings
		Absence of rumble strips

Table 9: Taxonomy of road infrastructure risks related to alignment - junctions.

Infrastructure element	General risk factor	Specific risk factor
Alignment - Junctions	**Interchange deficiencies**	Ramp capacity
		Ramp length
		Acceleration / deceleration lane length
		Absence of channelization
		Absence of access control
		Poor sight distance
	At-grade junctions deficiencies	High number of conflict points *hot topic*
		Type of junction[5] *hot topic*
		Skewness / junction angle *hot topic*
		Poor sight distance *hot topic*
		Gradient *hot topic*

Table 10: Taxonomy of road infrastructure risks related to traffic control - junctions.

Infrastructure element	General risk factor	Specific risk factor
Traffic control - Junctions	**Rail-road crossings**	Uncontrolled rail-road crossing
	Poor junction readability	Uncontrolled junction
		Misleading or unreadable traffic sign
		Absence of road markings
		Absence of marked crosswalks

3.3 RISK FACTOR CODED STUDIES

For the inclusion of each study in the DSS, the preparation of an accompanying "coding template" was required. The coding template was utilized **to record key data and metadata from individual studies**, as described in (Martensen et al., 2017). For each study, several pieces of information were coded in the template, as described in section 2.2.2 of this report.

In total, at least **243 studies on infrastructure related risk factors have been coded**. Some of the studies were coded for more than one risk factor, but all of this information was included in one coding template. Completed coding templates (one file per study) were uploaded to the DSS relational database. The 243 studies were linked to 44 of the 59 infrastructure-related risk factors. For the 15 remaining risk factors, not enough detailed studies were found to be able to complete any

[5] This topic aims to examine the risks associated with all different types of at-grade junctions.

coding templates to include in the DSS. Further explanations about this, including which risk factors, can be found in Section 3.4.

The tables that follow provide an overview of useful characteristiscs for the 243 studies that are included in the DSS.

Table 11 gives an overview o f the main sources of the 243 risk factor-related coded studies. In total, the studies originated from 75 different publication sources, the majority of which were journal papers, and a smaller number from other scientific documents (e.g. iRAP reports, conference proceedings).

Table 11: Sources of the studies included in the risk factor analysis

Source of studies	No. of studies
Accident Analysis & Prevention	82
Transportation Research Board Annual Meeting	25
Transportation Research Record: Journal of the TRB	24
Safety Science	10
Journal Of Safety Research	8
Transportation Research	5
Traffic Injury Prevention	4
International Road Assessment Programme (IRAP)	3
Journal Of Transportation Engineering	3
Journal Of Transportation Safety & Security	3
Procedia - Social And Behavioral Sciences	3
Analytic Methods In Accident Research	2
Health & Place	2
Highway Safety Research Center - Report	2
International Journal Of Pavement Engineering	2
ITE (Institute Of Transportation Engineers) Journal	2
Journal Of Advanced Transportation	2
Journal Of The American Planning Association	2
Journal Of Transport Geography	2
Ohio Department Of Transportation,Office Of Research And Development	2
Proceedings Of 6th Transport Research Arena	2
World Conference on Transport Research	2
Other*	53

* Each of these 53 studies came from a different publication source

Over 50% of the coded risk studies were from either the journal Acccident Analysis & Prevention or from Transportation Research Board-related publications (i.e. the TRB journal and the TRB annual meeting).

Figure 2 shows the range of publication years for the 243 risk-related coded studies. It can be seen that about 50% of the studies were published in the past 5 years (since 2012) and over 75% in the past 10 years (since 2007), so the majority of risk factor-related publications that the results of the synopses are based on are from relatively recent studies.

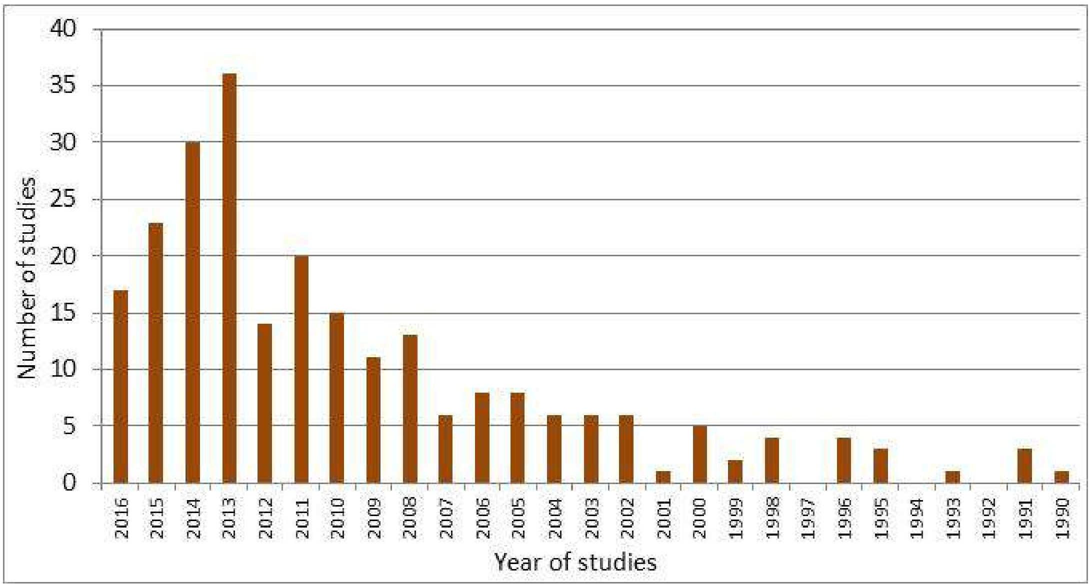


Figure 2: Year of publication of coded studies on infrastructure risk factors

Figure 3 highlights the countries of origin of the 243 risk-related coded studies and it shows that nearly half of the coded studies originated from the USA (49%), with 28% originating from Europe. The remaining studies were from a variety of countries across the rest of the world, including Asia and Australasia.

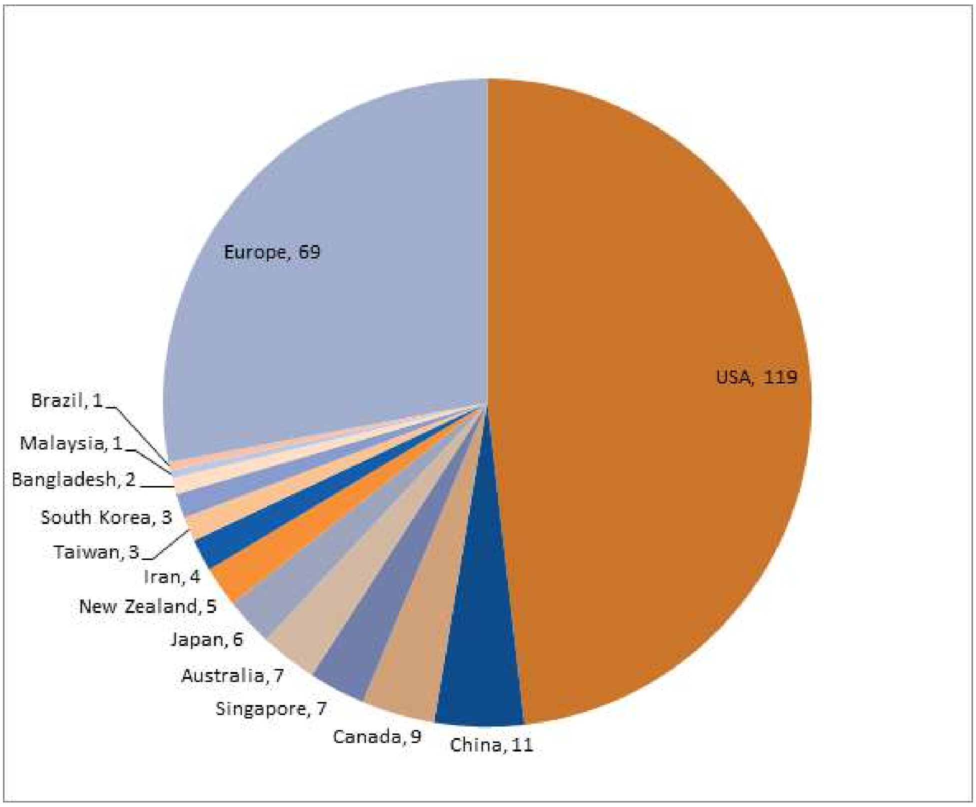


Figure 3: Number of coded studies originating from countries across Europe and the rest of the world which were included in the risk-related analyses

**The numbers add up to just over 243 as a small number of studies originiated from more than one country*

Across the 243 studies, a wide range of study methods were used for data analysis. **Table 12** highlights the types of methods used in the coded studies and their frequency, along with the number of risk factors that each type of method concerned. For example, observational studies were the most common type of study method found, being in 74% of the coded studies and present in 75% of risk factor topics. Cross-sectional studies were also found in a large number of studies and risk factor topics (54% and 72% respectively). Case-control studies were the 3rd most frequent study method type across studies in general and across risk-factor types.

Table 12: Types of studies coded across the risk factors and their frequency

Type of study method	Number of studies (out of 243)*	Number of Risk Factors (out of 44)**
Meta-analysis	6	5
Case control	32	12
Observational	180	33
Cross-sectional	131	32
Experimental	15	4
Quasi experimental	1	1
Simulation	8	6
Full Bayes	9	7
Empirical Bayes	3	2
Before-after	7	4
Longitudinal	1	1

Intervention modelling	2	2
Crossover/repeated measures	1	1
Time-series	17	2

*A study could include more than one method type (e.g. obesrvational & case-control), so the 'number of studies' column totals more than 243.

**Studies found for a specific risk factor could be of more than one type, so the 'number of risk factors' column totals more than 44.

In a large number of the 243 studies (46%), more than one method was used to analyse the data, and the most frequent study method combination was observational and cross-sectional study methods, which featured in 34% of the studies.

While most study methods were found in studies across a range of risk-factor types, the 17 time-series studies were only found for the two risk factors related to adverse weather conditions (rain and snow/ice/low temperatures) and the same was found for the 10 experimental studies (9 related to inadequate friction and 1 to skewness/junction angle).

As can be seen in **Table 13**, for the majority of the 44 risk factors (57%), there was one clear **exposure variable (i.e., the variable that quantifies or qualifies the exposure to a risk factor)** across all of the coded studies found for that risk factor, and it was often the name of the risk factor itself.

For example, for the risk factor 'ramp length' the measure of exposure was always ramp length. For some risk factors, the single exposure variable differed slightly from the risk factor name. For example, for 'undivided road', the measure of exposure was 'presence of median island'. So to measure 'undivided road' data, it would be split between conditions when a median island was present (i.e. exposed to the risk factor) and when a median island was not present (i.e. not exposed to the risk factor).

Table 13: Number of exposure variables per risk factor

Number of exposure variables per risk factor	Number of Risk Factors
1	25
2	10
3	4
4	2
5	1
>5	2

For the remaining 19 risk factors, there was found to be more than one measure of exposure described across the coded studies. For example, for the risk factor 'absense of paved shoulders', two measures of exposure were found in the coded studies, which were 'unpaved shoulders' and 'no shoulder'. For road surface – inadequate friction', there were five measures of exposure, which included 'pavement friction', 'pavement condition' (i.e. maintenance), 'surface type' and 'surface contaminants' (e.g. snow, wet...). This highlighted that some infrastructure-related risk factors were more complex to analyse than others, covering a wider range of conditions that could affect the outcome of a crash if the risk factor was present.

A look at the type of **outcome variables (i.e. variables that quantify or qualify the outcome of risk factors for road safety)** available across the coded studies for each risk factor was undertaken and the results are overviewed in **Table 14**.

Table 14: Types of outcomes examined across the risk factors

Type of Outcome	Number of Risk Factors
Accident rate/risk	41
Injury or casualty rate/risk	11
Vehicle speed/acceleration	7
Lateral position of vehicle	2
Road user type	2
Accident modification factor	2
Risk perception	2
Discomfort	2
Vehicle kms travelled	2
Driver fault	1
Braking length	1
Behaviour of drivers/pedestrians	1

Accident rate/risk was by far the most frequent measure of outcome across the coded studies and the 44 risk factors, with all but three risk factors having at least one coded study where accident rate/risk was the outcome variable. Some outcomes were related to the vehicles, such as speed, lateral position and kms travelled, but also related specifically to the road user, such as behaviour and also subjective outcomes, including discomfort and risk perception.

3.4 RISK FACTOR SYNOPSES

Where sufficient studies could be identified, a synopsis was written summarising the impact of the risk factor on road safety. Each synopsis has a common format which starts with a colour code indicating the level of evidence available as to the risk affected. This is followed by an abstract providing a summary of the findings for the examined risk factor (for details see section 2.2.3).

Ultimately **39 synopses on road infrastructure risk factors** have been developed for inclusion in the DSS. Some of them include results of existing meta-analyses, and four of them include results of **new meta-analyses** carried out within SafetyCube ('small workzone length', 'high workzone duration', 'insufficient ramp length' and 'insufficient acceleration / deceleration lane length'). This has been accomplished by 9 different SafetyCube partner organisations. It has to be noted that due to available studies and some contents of the synopses their titles were slightly adapted by the authors in certain cases.

Furthermore, it should be underlined that the results of the synopses included in this Deliverable are from the **final versions available at the time of the submission**, which have been thoroughly reviewed within the WP, and also within the project (Deliverables internal review procedures). Nevertheless, **the synopses are living documents**, which are being further improved after the Deliverable submission (e.g. if new studies are identified, if additional suggestions for improvement are received by project partners). Moreover, a thorough Quality Assurance procedure has been implemented for all the contents of the DSS before the end of the project. Therefore, any further improvements in the synopses included in this Deliverable will be reflected in the **final versions available in the DSS at the end of the project**.

Originally, it was intended that there would be a synopsis written for each of the 59 specific risk factors. But it was not possible for a synopsis to be written for 20 risk factors as explained further below:

- Road Surface (Road surface deficiencies): One synopsis for road surface was produced at the risk factor level (titled 'inadequate friction'), rather than for each specific risk factor (i.e. 1 synopsis instead of 4).
- Wind (Adverse weather): The synopsis for wind could not be completed due to insufficient identified studies.
- Insufficient signage (Workzone): The synopsis for insufficient signage could not be completed due to insufficient identified studies.
- Vertical curve radius (Alignment - road segments): The synopsis for vertical curve radius could not be completed due to insufficient identified studies.
- Poor sight distance – Horizontal curves and Vertical curves (Alignment - road segments): The two synopses for poor sight distance – horizontal and vertical curves could not be completed due to insufficient identified studies (i.e. 0 synopses instead of 2).
- Cross-slope (Cross-section - road segments: super elevation/cross slopes): The synopsis for cross-slope could not be completed due to insufficient identified studies (i.e. 1 synopses instead of 2). Some information on cross-slopes is available in the related synopsis on 'superelevation'.
- Shoulder and roadside deficiencies – absence of guardrails/crash cushions, absence of clear zone, roadside obstacles and risks associated with safety barriers and obstacles (Cross-section - road segments): Three synopses are under development covering (i) 'risks associated with safety barriers, (ii) 'risks associated with obstacles' and (ii) 'sight obstructions (Landscape, Obstacles and Vegetation)' (i.e. 3 synopsis instead of 4). These are still under revision at the time of submission of this report.
- Traffic control - road segments, Poor road readability: No synopses were produced for any specific risk factors because of the difficulty separating risks from measures (i.e. 0 synopses instead of 4). This topic was considered when measures were evaluated (see Chapter 4).
- Absence of channelisation, ramp capacity and poor sight distance (Alignment – junctions: interchange deficiencies): The synopses for these three topics could not be completed due to insufficient identified studies (i.e. 3 synopses instead of 6).
- Misleading or unreadable traffic sign (Traffic control – junctions): The synopsis for misleading or unreadable traffic sign could not be completed due to insufficient identified studies (i.e. 4 synopses instead of 5).
- Absence of road markings and absence of marked crosswalks (Traffic control – junctions): One synopsis was developed covering both absence of road markings and absence of marked crosswalks (i.e. 1 synopsis instead of 2). The topis are analysed from a road safety measure viewpoint (see Chapter 4).

For five of the above risk factor topics ('horizontal curves', 'uneven surface', 'ice, snow', 'cross-slopes' and 'insufficient signage'), although no synopsis was written due to insufficient number of studies found or low quality papers, some coding templates were completed (approximately 12 studies across the 5 risk factor topics) and included in the DSS without a synopsis.

Table 15 provides a summary for the coded studies per taxonomy topic (i.e. risk factor) and the total number of effects analysed for the topics where a synopsis was written.

Table 15: Number of studies and effects per synopses

Infrastructure element	Risk factor	Specific risk factor	No. of studies*	Total no. of effects
Exposure	Traffic flow	Traffic volume	7	33
		Congestion	7	6
		Secondary incidents / accidents	7	25
		Traffic composition (share of pedestrians, cyclists, PTW, HGV)	6	48
		Distribution of flow over arms at junctions	8	23
Road type	Road functional class	Road functional class	5	15
Road surface	Road surface deficiencies (risk of ran-off road)	inadequate friction	16	15
		*Uneven surface***	*2*	*N/K****
		Ice, snow	*4*	*N/K*
Road environment	Poor visibility and lighting	Poor visibility - darkness	5	46
		Poor visibility - fog	4	30
	Adverse weather	Rain	14	84
		Snow / ice / low temperatures	10	88
Workzones	Workzones	Small workzone length	8	17
		High workzone duration	5	10
		Insufficient signage	*3*	*N/K*
Alignment - Road segments	Horizontal/vertical alignment deficiencies	Low curve radius	5	0
		Absence of transition curves	4	0
		Frequent curves	3	23
		Densely spaced junctions	5	23
		Horizontal curves	2	N/K
		High grade	13	92
		Tunnel	6	34
Cross-section - Road segments	Superelevation / cross-slopes (risk of ran-off road)	Superelevetion at curve	4	32
		Cross-slope	*1*	*N/K*
	Lanes / ramps deficiencies	Number of lanes	5	141
		Narrow lane	5	80
	Median / barrier deficiencies (risk of crash with oncoming traffic)	Undivided road	3	13
		Narrow median	5	14
	Shoulder and roadside deficiencies (risk of ran-off road or crash with obstacle)	Absence of shoulder	5	30
		Narrow shoulder	5	55
		Risks associated with safety barriers	under revision	
		Risks associated with obstacles	under revision	
		Sight obstructions	5	41
Alignment-junctions	Interchange deficiencies	Insufficient ramp length	8	10
		Insufficient acceleration / deceleration lane length	10	33

Infrastructure element	Risk factor	Specific risk factor	No. of studies*	Total no. of effects
		Absence of access control	4	9
	At-grade junctions deficiencies	High number of conflict points	13	65
		Type of junction	19	55
		Skewness / junction angle	12	25
		Poor sight distance	7	15
		Gradient	8	14
Traffic control - junctions	Rail-road crossings (risk of collision with train)	Uncontrolled rail-road crossing	9	17
	Poor junction readability	Uncontrolled junction	8	25
		Absence of road markings & crosswalks	11	21
Total			304	1367

*The number of studies in this table totals 304, which is more than the 243 studies coded because some studies being coded for more than one risk factor.

** The shaded risk factors are those where studies have been coded, but no synopsis was written, due to insufficient /low quality studies

***N/K = The number of effects for these risk factors is unknown as this information was retrieved from the synopses and no synopses were written for these topics.

For some risk factors, it was possible to undertake a meta-analysis using the studies found related to the topic, whereas for others, a vote-count analysis was deemed to be a more valid study to undertake. And where neither a vote-count nor meta-analysis was possible, a review-style analysis was undertaken to provide an overview of the studies found. **Table 16** shows the number of meta-analsyes, vote count and review-type analyses carried out across the 39 risk factors where a synopses was written.

Table 16: Types of analysis carried out in the 39 infrastructure-related risk factor synopses

Type of Analysis	Number of Synopses/risk factors
Meta-analysis	4
Vote count	19
Review analysis	16

As mentioned previously, for four of the risk factor topics, a meta-analysis was undertaken. The topics were 'small workzone length', 'high workzone duration', 'insufficient ramp length' and 'insufficient acceleration / deceleration lane length'. None of these risk factors topics included existing meta-analysis studies, so the studies for each topic were brought together to create complete new meta-analyses. When undertaking these meta-analyses, the results led to the conclusion that insufficient workzone length did increase accident risk, whereas the results implied that insufficient ramp length was probably risky and that workzone duration had unclear results in terms of accident risk, as did acceleration and deceleration lane lengths.

The most frequent type of analysis across the 39 infrastrcture-related risk factor synopses a vote-count analysis, which was undertaken for just under 50% of the topics (19). As part of the vote-count, tables were produced which showed the proportion of reported effects across all the studies for each risk factor which showed (i) a statistically significantly increase in risk to safety, (ii) a significant decrease in risk to safety, and (iii) no significant difference in terms of safety (i.e. either a non-significant result or statistical analysis was not undertaken). **Figure 4** provides an **overview of the proportion of the negative, positive and non-significant effects on safety** for each of the 19 risk factor topics where a vote count was undertaken.

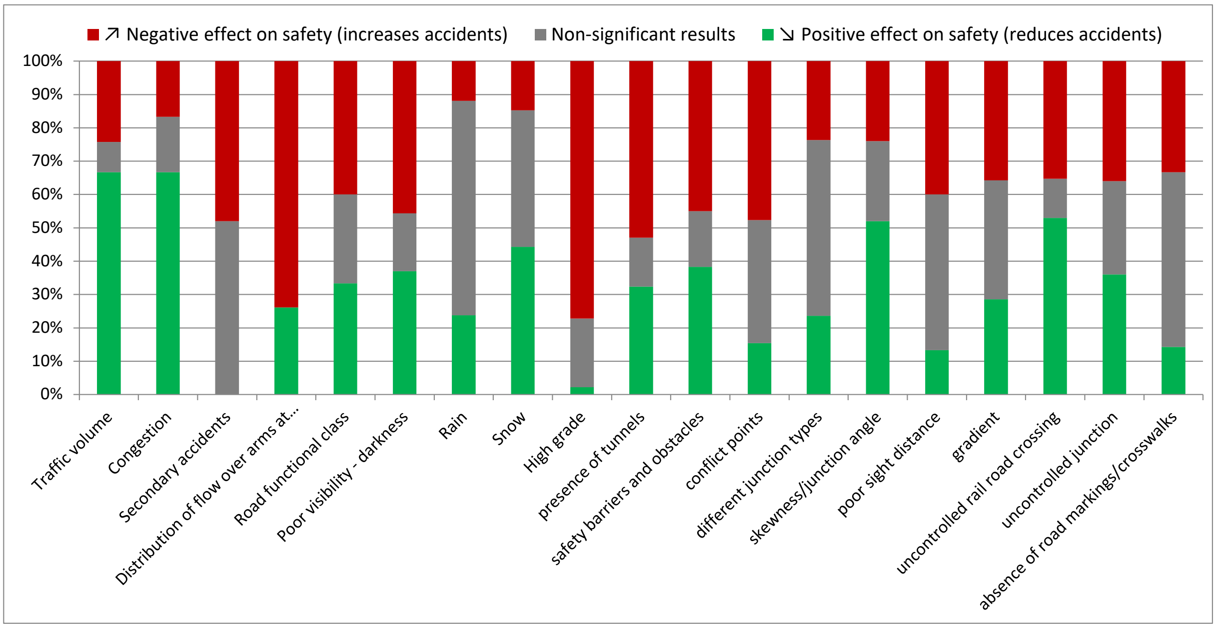


Figure 4: Results of vote-count analyses undertaken for the 19 infrastructure-related risk factor topics

Figure 4 shows that the risk factors with the greatest proportion of negative effects on safety were 'distribution of flow over arms at junctions' and 'high grade' (i.e. uphill or downhill). In other words, over 70% of the effects analysed in studies related to these two topics showed a negative effect on safety (i.e. an increased accident risk). So, for example, the presence of a high grade was more often found to increase accident risk.

'Traffic volume' and 'congestion' were found to be the two risk factor topics which resulted in the greatest proportion of positive effects on safety. In both cases, over 65% of effects were found to reduce accident risk. This is not surprising, as both high traffic volume and traffic congestion will inevitably lead to lower vehicle speeds, which in turn will reduce the risk of accidents occurring, as vehicle speed has been found to have a high correlation wth accident risk (Taylor et al, 2000).

Some risk factor topics had a high number of non-significant results, particularly topics, such as 'rain', 'secondary accidents', 'different junction types' and 'absence of road markings/crosswalks', which all had over 50% of effects which were non-significant (or no statistical analysis carried out). Therefore, for these topics, it is less clear from the vote-count analysis whether they have an overall positive or negative on safety. In some cases, e.g. 'rain', there were significantly different effects found for different road user groups, hence similar shares of "opposite" results. Although for secondary accidents, there was found to be no positive effects on safety, making it more likely that this risk factor will lead to increased accident risk. However, to determine the final colour code for each risk factor, more than the results of the vote-count analysis were considered (e.g. quality of studies, transferability potential…), and this will be reflected in the final colour codes outlined in section 3.5.

For the final 16 synopses where neither a meta-analysis nor a vote-count could be undertaken, a review-type analysis was instead carried out to provide a general overview of the studies found for the specific risk factor topic and any general conclusions that could be made. The results of these review-type analyses can be found in Filtness et al. (2016).

3.5 MAIN RESULTS FROM RISK FACTOR EVALUATION

Overall, of the 59 original infrastructure-related risk factor topics identified, it was possible to write a synopsis for 39 of them. It was possible for an additional 5 topics to have a small amount of coded studies (12 in total) in the DSS but no synopsis. It was not possible to code any studies or write a synopsis for the remaining 15 risk factor topics.

Table 17 presents the risk factors synopses respectively separated by colour code. In total:

- 11 risk factors were given the colour **Red, indicating that there is consistent evidence** that they have a negative effect on road safety in terms of increasing crash risk (e.g. average number of crashes per unit of exposure), frequency or severity (i.e. severity of the casualty injuries involved in each crash).
- Eighteen measures were marked as yellow (probably risky) with a likely negative effect on road safety.
- Grey (unclear) was assigned to 7 risk factors, where no clear conclusion could be drawn.
- For three risk factors, more than one colour code was assigned, as it was concluded that the risk factor presented a different level of risk to different road user types according to the literature found. These were 'Traffic composition', 'Rain' and 'Darkness' and underlined in **Table**.
  - For 'Traffic composition', it was considered to be risky (red) when the traffic composition includes Vulnerable Road Users (VRUs) (i.e. a mix of VRU and motorised vehicles), but the level of risk was unclear (grey) when HGVs were included in the traffic composition.
  - For 'Rain', it was concluded that it was risky (red) for motor vehicles, but the risk to other road user types was unclear (grey). When all vehicle types were considered together, rain was considered to be probably risky (yellow).
  - For 'Darkness', it was concluded that it was probably not risky (green) for cars, although for pedestrians, it was considered to be risky (red). For two-wheeled vehicles and when considering all road user types together, it was considered to be probably risky (yellow).

A detailed overview of the infrastructure related risk factor topics is presented in **Table 18**. Results are separated for each of the infrastructure element, with the specific risk factors within each element **ranked by colour code and indication on the type of road safety outcomes affected, whether or not this is a hot topic as well as the studied road types.** Finally, the remarks column indicates conditions where an effect was maximized or differentiated from the majority.

The majority of the risk factors in Table 18, were investigated in all road types (i.e. motorways, urban and rural roads). Ten measures were implemented on rural and urban roads, whereas motorways and rural roads concerned eight measures. Five measures (i.e. volume, secondary crashes, ramp length, acceleration/deceleration lane length and uncontrolled rail junctions) were studied only on motorways, while the effect of traffic composition for VRUs and densely spaced junctions were analysed only on urban roads.

Table 17: Infrastructure related risk factors synopses by colour code

Red (Risky)	Yellow (Probably risky)	Grey (Unclear)	Green (Probably not risky)
! **Effect of Traffic Volume on safety** ! **Risks associated with Traffic Composition (VRUs only)*** ! **Road Surface - Inadequate Friction** ! **Poor Visibility – Darkness (pedestrians only)*** ! **Adverse weather – Rain (motor vehicles only)*** ! **Workzone length** ! **Alignment deficiencies - Low Curve Radius** ! **Cross-section deficiencies - Number of Lanes** ! **Shoulder and roadside deficiencies -Absence of paved shoulders** ! **Shoulder and roadside deficiencies - Narrow Shoulders** ! **Interchange deficiencies – absence of access control** ! **At-grade junction deficiencies - Risk of different junction types** ! **At-grade junction deficiencies - Gradient** ! **Uncontrolled rail-road crossing**	! Congestion as a risk factor ! Occurrence of Secondary crashes ! Alignment deficiencies - Absence of Transition curves ! Road functional class ! Poor Visibility – Darkness (all and two-wheelers only)* ! Poor visibility – fog ! Adverse weather – Rain (all)* ! Workzone duration ! Alignment deficiencies - High grade ! Presence of Tunnels ! Cross-section deficiencies - Superelevation ! Cross-section deficiencies - Narrow lanes ! Undivided road ! Cross-section deficiencies - Narrow median ! Shoulder and roadside deficiencies - Risks associated with Safety Barriers and Obstacles ! Shoulder and roadside deficiencies - Sight Obstructions (Landscape, Obstacles and Vegetation) ! At-grade junctions deficiencies - Number of conflict points ! At-grade junction deficiencies - Skewness / Junction angle ! At-grade junction deficiencies - Poor sight distance ! Poor junction readability - Uncontrolled junction	? Risks associated with Traffic Composition (HGVs only)* ? Risks associated with the distribution of traffic flow over arms at junctions ? Adverse weather – Rain (other road users only)* ? Adverse weather - Frost and snow ? Alignment deficiencies - Frequent curves ? Alignment deficiencies - Densely spaced junctions ? Interchange deficiencies - Ramp Length ? Interchange deficiencies - Acceleration / deceleration lane length ? Poor junction readability - Absence of road markings and crosswalks	✓ Poor Visibility – Darkness (cars only)*

*The risk factors which are underlined have more than one colour code, but for different road user types.

Table 18: Overview of the results on infrastructure related risk factors to crashes

Infrastructure Element	Specific Risk Factor	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional remarks
							Motorways	Rural roads	Urban roads	
Exposure	Effect of traffic volume on safety	Red	↓	↑	-	N	✓			Multi-vehicle crashes appear to incresae more
	Risks associated with traffic composition (risk to VRUs only)***	Red	↓	↑	-	N			✓	
	Occurrence of secondary crashes	Yellow	↑	-	-	N	✓			Long incident duration, daytime and peak period incidents increase the probability of a secondary crash
	Congestion as a risk factor	Yellow	-	↑	-	N	✓	✓	✓	Delay or low speed is associated with high crash frequency for all crash types
	Risks associated with traffic composition (risk to HGVs only)***	Grey	↓	↑	-	N	✓	✓		
	Risks associated with the distribution of traffic flow over arms at junctions	Grey	-	-	↑	N		✓	✓	More negative effects on signalised juctions than on non-signalised ones
Road Type	Road Functional Class	Yellow	-	↑	↑	N	✓	✓	✓	For heavy track tractors, high speed national roads have the greatest risk
Road Surface	Inadequate Friction	Red	↑	-	↑	N	✓	✓	✓	Pavement surface skid resistance can improve safety of urban intersections
	Uneven surface	N/A	One synopsis for road surface was produced at the risk factor level (titled 'inadequate friction'), rather than for each specific risk factor due to minimal studies in this area.							
	Ice, snow	N/A								

Infrastructure Element	Specific Risk Factor	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional remarks
							Motorways	Rural roads	Urban roads	
	Oil, leaves, etc.	**N/A**	Separate coded studies for uneven surface (2) and ice/snow (4) were included in the DSS.							
Road environment	Adverse weather - Rain (risk to motor vehicles only)***	**Red**	-	↑	-	N	✓	✓	✓	-
	Poor Visibility - Darkness (risk to pedestrians only)***	**Red**	↑	-	↑	N	✓	✓	✓	The crash risk for pedestrian is 2 to 4 times higher in darkness
	Adverse weather - Rain (risk to all)***	**Yellow**	-	↑	-	N	✓	✓	✓	85% of the studies found an increase in fatal crashes, mostly in motorways and rural roads
	Poor Visibility - Darkness (risk to all and risk to two-wheelers only)***	**Yellow**	↑	-	↑	N	✓	✓	✓	The risk of crash in darkness increasing only in urban areas for PTW
	Poor visibility - Fog	**Yellow**	-	↑	-	N	✓	✓	✓	
	Adverse weather - Frost and Snow	Grey	-	-	-	N	✓	✓	✓	Frost tends to increase crash risks on motorways. First snow is asssociated with higher crash risk
	Adverse weather - Rain (ris k to other road users only)***	Grey	-	↑	-	N	✓	✓	✓	-
	Poor Visibility - Darkness (risk to cars only)***	**Green**	↑	-	↑	N		✓	✓	-
	Adverse weather - Wind	**N/A**	The synopsis for wind could not be completed due to insufficient identified studies.							
Presence of workzones	Workzone Length	**Red**	↑	↑	-	**Y**	✓	✓	✓	-
	Workzone Duration	**Yellow**	-	-	-	**Y**	✓	✓	✓	-

Infrastructure Element	Specific Risk Factor	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied: Motorways	Road types studied: Rural roads	Road types studied: Urban roads	Additional remarks
	Insufficient signage	N/A	The synopsis for insufficient signage could not be completed due to insufficient identified studies. However, 3 coded studieswere included in the DSS.							
Alignment - Road Segments	Low Curve Radius	Red	-	↑	↑	Y	✓	✓		Different CMF results between USA and European studies
	Alignment deficiencies - Absence of transition curves	Yellow	↑	-	-	Y	✓	✓		-
	Alignment deficiencies - High Grade	Yellow	-	↑	↑	Y	✓		✓	-
	Presence of Tunnels	Yellow	-	↑	↑	Y	✓	✓		-
	Alignment deficiencies - Frequent curves	Grey	-	-	-	Y		✓	✓	-
	Alignment deficiencies - Densely spaced junctions	Grey	-	-	-	Y			✓	Improvement on pedestrian safety but high crash risk for cars and other road users
	Alignment deficiencies – Vertical curve raduis	N/A	The synopsis for these risk factors could not be completed due to insufficient identified studies. However, 2 studies for horizontal curves were included in the DSS.							
	Poor sight distance – Horizontal curves	N/A								
	Poor sight distance – Vertical curves	N/A								
Cross-Section - Road Segments	Cross-section deficiencies - Number of lanes	Red	-	↑	↑	N	✓	✓	✓	A positive effect was indicated only for a mountaineous motorway under adverse weather conditions

Infrastructure Element	Specific Risk Factor	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional remarks
							Motorways	Rural roads	Urban roads	
	Shoulder and roadside deficiencies - Absence of paved shoulders	Red	-	↑	-	Y	✓	✓		-
	Shoulder and roadside deficiencies -Narrow shoulders	Red	-	↑	-	Y	✓	✓		-
	Cross-section deficiencies - Narrow lanes	Yellow	-	↑	-	N	✓	✓	✓	-
	Undivided Road	Yellow	-	-	↑	N		✓	✓	-
	Cross-section deficiencies - Narrow Median	Yellow	-	↑	↑	N	✓	✓	✓	Increased crash frequency for women and older drivers. IF median width is less than 40 feet the no-injury crash rate decreases
	Shoulder and roadside deficiencies - Risks associated with safety barriers (under revision)	Yellow	-	↑	↑	Y	✓	✓		Colliding with a steel type compared to concrete type guardrail appears to increase the risk of fatality, but reduces the risk of injury
	Shoulder and roadside deficiencies - Sight obstructions (Landscape, Obstacles and Vegetation)	Yellow	-	-	-	Y	✓	✓	✓	The wider the offsets of the trees from the edge of the road pavement is on rural area, the higher the crash risk
	Cross-section deficiencies - Superelevation	Yellow	↑	↑	-	N	✓	✓		-
	Cross-section deficiencies - Cross-slope	N/A	The synopsis for cross-slope could not be completed due to insufficient identified studies. However, 1 coded study was included in the DSS.							

Infrastructure Element	Specific Risk Factor	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional remarks
							Motorways	Rural roads	Urban roads	
	Shoulder and roadside deficiencies - Absence of guardrails or crash cushions	**N/A**	'Absence of guardrails/crash cushions', 'absence of clear zone', 'absence of roadside obstacles' and 'risks associated with safety barriers and obstacles' were replaced with two synopses covering 'all 'risks associated with safety barriers and obstacles' and 'sight obstructions (Landscape, Obstacles and Vegetation).							
	Shoulder and roadside deficiencies - Absence of clear zone	**N/A**								
Traffic control – Road segments	Absence of traffic signs	**N/A**	No synopses were produced for these risk factors because of the difficulty of separating risks from measures.							
	Misleading or unreadable traffic signs	**N/A**								
	Absence of road markings	**N/A**								
	Absence of rumble strips	**N/A**								
Alignment - Junctions	Interchange deficiencies - Absence of access control	**Red**	-	↑	-	N	✓	✓	✓	-
	Risk of different junction types	**Red**	↑	-	↑	**Y**		✓	✓	4-legged junctions more unsafe than 3-legged ones and roundabouts more safe than intersections
	At-grade junction deficiencies - Gradient	**Red**	↑	-	↑	N		✓	✓	Junctions located at a (constant) grade are associated with a higher fatality risk
	At-grade junctions deficiencies - Number of conflict points	**Yellow**	-	↑	-	**Y**		✓	✓	-

Infrastructure Element	Specific Risk Factor	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied: Motorways	Road types studied: Rural roads	Road types studied: Urban roads	Additional remarks
	At-grade junction deficiencies - Skewness / junction angle	Yellow	↑	-	↑	Y		✓	✓	A skewed angle at intersections appears to lead to a higher crash risk compared to an intersection angle of 90 or near 90 degrees
	At-grade junction deficiencies - Poor Sight Distance	Yellow	↑	-	-	Y		✓	✓	-
	Interchange deficiencies - Ramp length	Grey	-	-	↑	N	✓			-
	Interchange deficiencies - Acceleration/Deceleration lane length	Grey	-	-	-	N	✓			There is an indication that increased deceleration lane length leads to more crashes (although less severe)
	Interchange deficiencies – Absence of channelisation	N/A	The synopses for these three topics could not be completed due to insufficient identified studies.							
	Interchange deficiencies – Ramp capacity	N/A								
	Interchange deficiencies – Poor sight distance	N/A								
Traffic Control - Junctions	Uncontrolled rail-road crossing	Red	↑	-	↑	N	✓			-
	Poor junction readability - Uncontrolled junctions	Yellow	-	↓	↑	N	✓	✓	✓	-
	Poor junction readability - Absence of road markings and crosswalks	Grey	-	-	↑	N		✓	✓	-
		One synopsis was developed covering the two risk factors of absence of road markings and absence of marked crosswalks.								

Infrastructure Element	Specific Risk Factor	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional remarks
							Motorways	Rural roads	Urban roads	
	Misleading or unreadable traffic sign	**N/A**	The synopsis for misleading or unreadable traffic sign could not be completed due to insufficient identified studies.							

* Crash risk –number of crashes per unit of exposure.
** Crash severity – the severity of the injuries sustained by the casualties involved in the crashes
***These risk factors have more than one colour code, but for different road user types.

4 Road infrastructure safety measures

This chapter shows which are the road infrastructure measures addressed in the inventory, how results are presented, the type of information the DSS user will find in a coded template, the type of information the DSS user will find in a synopsis, and a summary of the results.

4.1 WHAT IS A MEASURE?

Within the SafetyCube project **'measure' refers to any intervention that is taken to reduce the risk, the frequency or the consequences of road accidents'**. Measures can have a direct influence on the risk or the frequency of an accident occurring, on the consequences of the accident (e.g. severity), or more indirectly by influencing a Safety Performance Indicator (SPI) which itself has a causal link to crashes or severity (e.g. speed); this, however, is often difficult to observe in isolation.

During the first steps of the analysis, we noticed **a high degree of duality between risks & measures** in the infrastructure domain: the absence of a specific measure often poses a risk, e.g. a missing median barrier increases the risk of head-on collisions. An example of this duality can be seen if we consider an ill-designed cross-section of a road (lanes too wide or too narrow for a given setting) which can pose a risk, although modifying these lane widths can also be an effective safety measure. Hence many, if not all, elements of the road system are potential crash risk factors *and* measures, depending on the point of view from which they are examined. This report, however, deals exclusively with measures that are related to the design and layout of the road infrastructure. Methodological implications are discussed in section 5.2.

4.2 ROAD SAFETY MEASURES ADDRESSED

The first step in order to be able to identify and rank infrastructure related measures in terms of their impact on accident causation was the development of **a taxonomy,** a process corresponding to the one for risk factors which was described in Chapter 3, using the same resources and publications.

Eventually, **94** specific measures within **24** general measures, all within **11** infrastructure elements, have been identified. In particular, a hierarchical taxonomy was created, with infrastructure elements (i.e. general topics) including several general measures, and in several cases each general measure may include many specific measures.

The **types of infrastructure** covered in the SafetyCube taxonomy include those described in Chapter 3 for risks. We opted not to further distinguish measures per road type in the taxonomy, but address each measure for all relevant road types.

The tables below illustrate the entirety of the taxonomy utilised in infrastructure analyses of the SafetyCube project. General categories of infrastructure elements were firstly considered and then the specific measures were assigned to the respective element and general measures. Tables include information on the hot topics too. **Measures indicated by stakeholders as 'hot topics' are highlighted in orange**. The **infrastructure elements** that are included are summarized below, while **Tables 19-29** give an overview of the measures taxonomy. There is significant overlap with the risk factor taxonomy, as expected, but there are also some different fields e.g. Infrastructure Safety Management.

- Exposure.
- Infrastructure safety management.
- Road type.
- Road surface.
- Lighting.
- Workzones.
- Alignment - Road segments.
- Cross-section - Road segments.
- Traffic control - Road segments.
- Alignment - junctions.
- Traffic control - junctions.

Table 19: Taxonomy of road infrastructure measures related to exposure.

Infrastructure element	General measure	Specific measure
Exposure	**Traffic flow**	Flow diversion
		2 + 1 roads
		Reversible lanes
		One-way traffic
		Ramp metering
		Access control
	Traffic composition	HGV traffic restrictions
		Creation of HGV lanes

Table 20: Taxonomy of road infrastructure measures related to infrastructure safety management.

Infrastructure element	General measure	Specific measure
Infrastructure safety management	**Formal tools to address road network deficiencies** *hot topic*	Road safety audits implementation
		Road safety inspections implementation
		High risk sites identification
		Land use regulations improvement
	Speed management & enforcement	Reduction of speed limit
		Dynamic (weather-variant) speed limits *hot topic*
		Individual Dynamic Speed Warning *hot topic*
		Speed cameras[6]
		Section control
		Speed humps
		Woonerfs implementation
		Narrowings
		School zones
		30-zones implementation
		Traffic calming schemes

Table 21: Taxonomy of road infrastructure measures related to road type.

Infrastructure element	General measure	Specific measure
Road type	**Road type**	Upgrade / downgrade road class
		Upgrade road to motorway
		Creation of by-pass road

Table 22: Taxonomy of road infrastructure measures related to road surface.

Infrastructure element	General measure	Specific measure
Road surface	**Road surface treatments**	Improve friction (type of surface)
		Road re-surfacing to improve evenness
		Ice prevention / winter maintenance

[6] The effects of speed enforcement measures in general were analysed in SafetyCube WP4-Behaviour; however, means of speed enforcement related to the road infrastructure, such as speed cameras, were explicitly analysed in WP5.

Table 23: Taxonomy of road infrastructure measures related to lighting.

Infrastructure element	General measure	Specific measure
Lighting	**Visibility / Lighting treatments** *hot topic*	Installation of road lighting
		Improvement of existing lighting

Table 24: Taxonomy of road infrastructure measures related to workzones.

Infrastructure element	General measure	Specific measure
Workzones	**Workzones** *hot topic*	Workzone signage installation
		Workzone signage improvement
		Workzone length treatment
		Workzone duration decrease

Table 25: Taxonomy of road infrastructure measures related to alignment - road segments.

Infrastructure element	General measure	Specific measure
Alignment - Road segments	**Horizontal & vertical alignment treatments**	Creation of weaving areas
		Increase horizontal curve radius (curve re-alignment)
		Implement transition curves (curve re-alignment)
		Reduce number of curves (re-alignment)
		Reduce tangent length
		Sight distance treatments (horizontal alignment)
		Reduce gradient (re-alignment)
		Increase vertical curve radius (curve re-alignment)
		Sight distance treatments (vertical alignment)

Table 26: Taxonomy of road infrastructure measures related to cross-section - road segments.

Infrastructure element	General measure	Specific measure
Cross-section - Road segments	**Superelevation / cross-slopes treatments**	Superelevation improvement
		Cross-slope improvement
	Lanes / ramps treatments	Increase number of lanes
		Increase lane width
		Create speed change lane
	Median / barrier treatments	Installation of median
		Increase median width
		Change median type
		Implementation of rumble strips at centerline
	Shoulder & roadside treatments *hot topic*	Shoulder implementation (shoulder type)
		Increase shoulder width
		Change shoulder type
		Safety barriers installation
		Change type of safety barriers
		Create clear-zone / remove obstacles
		Increase width of clear-zone
		Removal of sight obstructions
	Delineation and road markings	Road markings implementation
		Installation of chevron signs
		Implementation of edgeline rumble strips
		Transverse rumble strips
	Sidewalk treatments	Sidewalk installation
		Increase of sidewalk width
	Cycle lanes	Cycle lane treatments
		Cycle path treatments
		Increase of cycle lane width

Table 27: Taxonomy of road infrastructure measures related to traffic control - road segments.

Infrastructure element	General measure	Specific measure
Traffic control – Road segments	**Traffic signs treatments** *hot topic*	Traffic sign installation
		Traffic sign maintenance
	Driver information and alert	Variable message sign: incident / accident warning
		Variable message sign: congestion / queue warning
		V2I schemes

Table 28: Taxonomy of road infrastructure measures related to alignment-junctions.

Infrastructure element	General measure	Specific measure
Alignment-junctions	**Interchanges treatments**	Convert at-grade junction to interchange
		Increasing ramp width
		Increasing ramp curve radius (ramp re-alignment)
		Increasing acceleration / deceleration lane length
		Increasing lane width
	At-grade junctions treatments	Channelisation
		Sight distance treatments *hot topic*
		Convert junction to roundabout
		Convert 4-leg junction to staggered junction
		Improve skewness / junction angle *hot topic*

Table 29: Taxonomy of road infrastructure measures related to traffic control - junctions.

Infrastructure element	General measure	Specific measure
Traffic control - junctions	**Rail-road crossings**	Rail-road crossing traffic sign
		Automatic barriers installation
	Traffic signs treatments	STOP / YIELD signs installation
		STOP / YIELD signs replacement
	Road markings	Road markings implementation
		Implementation of marked crosswalk
	Traffic signals treatments	Traffic signals installation
		Improve traffic signals timing
		Implementation of pedestrian signal phase

4.3 ROAD SAFETY MEASURES CODED STUDIES

For the inclusion of each study in the DSS, the preparation of an accompanying "coding template" was required. The coding template was utilized to record key data and metadata from individual studies, as described in (Martensen et al., 2017) and was developed in WP3. The process is described in chapter 2.2.

Completed coding templates (one file per study) were uploaded to the DSS relational database. In total, **more than 250 studies on infrastructure related measures** have been coded. The Tables that follow provide a summary for the coded studies per taxonomy topic as well as an overview of additional useful characteristiscs. It should be noted that study totals are not equal in the tables, due to some studies having fluctuating characteristics. For instance, one study might examine data from several countries (particularly true in Meta-analyses), investigate different outcomes (accident rate and vehicle speed) and can be included in more than one measure factors.

Coded studies originated from various sources, which were mainly scientific journals. **Table 30** provides an overview of the studies included in the measures analysis. A fair amount of dispersal of sources can be observed for the studies, the majority of which originated from papers of scientific journals/conferences.

Table 30: Sources of the studies coded and included in the measure synopses

Source of studies	Number of studies
Accident Analysis & Prevention	53
Transportation Research Record - TRR	35
Transportation Research Board - TRB	14
Traffic Injury Prevention	6
Journal of Transportation Safety & Security	5
Journal Of Safety Research	5
Transportation Research Part F: Traffic Psychology and Behaviour	4
ITE (Institute Of Transportation Engineers) Journal	4
Australian Road Research Board ARRB	4
Journal Of Transportation Engineering	4
Safety Science	3
British Journal of Occupational Therapy	3
Transport Research Arena - TRA	2
Transportation Research Procedia	2
TAC/ATC Conference	2
Transportation Research Part C: Emerging Technologies	2
Conference of the Canadian Society for Civil Engineering	2
International Conference: Traffic Safety on Three Continents	2
Other scientific journals/conferences	24
Scientific Books	4
Technical reports (High quality)	35
Misc.	4

As with the risk factor analysis, a considerable proportion of studies (47%) originate from either the journal Acccident Analysis & Prevention or from Transportation Research Board-related publications (i.e. the TRB journal - TRR and the TRB annual meeting - TRB).

Similarly, **Figure 5** provides an overview of the years those studies were published. Once again, it can be seen that about 50% of the studies were published in the past 5 years (since 2012) and over 75% in the past 10 years (since 2007), so the majority of measure-related publications that the results of the synopses are based on are from relatively recent studies. It is also apparent that some publications before 1990 were included, either because they are considered too critical and still valid documents or for lack of other sources.

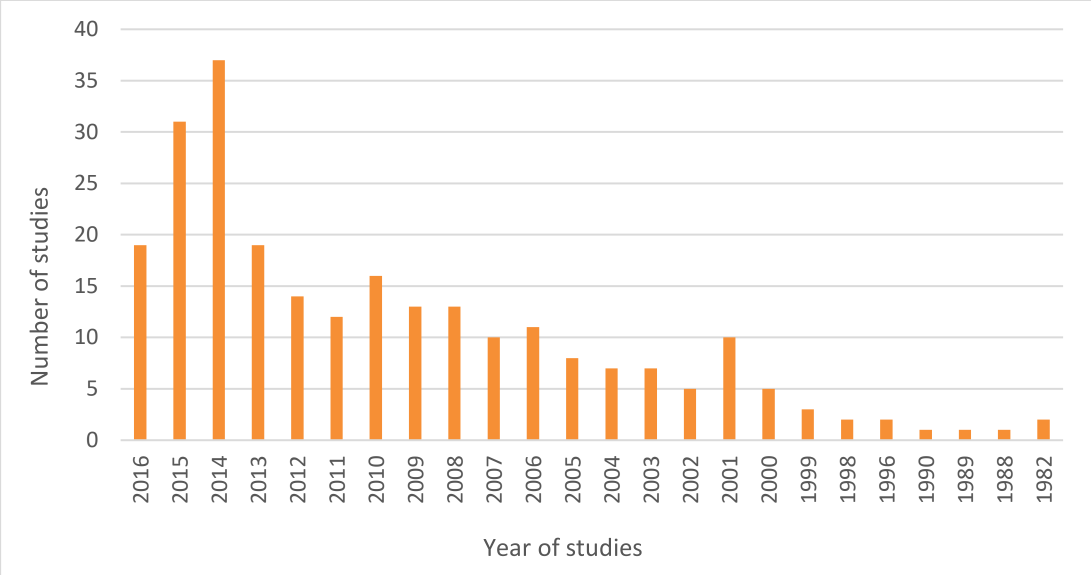


Figure 5: Year of publication of studies included in the measures analysis

For additional descriptive statistics, **Figure 6** provides an overview of the countries examined in the studies. Reasonably, Europe (geographical definition; i.e. including countries not in the EU such as Norway) and USA were major study sources, which were complemented by other areas of the globe. It should be noted that the "other" category comprises countries with 3 studies or less from countries not in Europe. The SafetyCube methodology prioritized European studies over others, but even excluding Europe, it can be discerned that overall the studies originate from or investigate more developed and motorized countries, and thus the rest of the countries have more ground to cover in that regard.

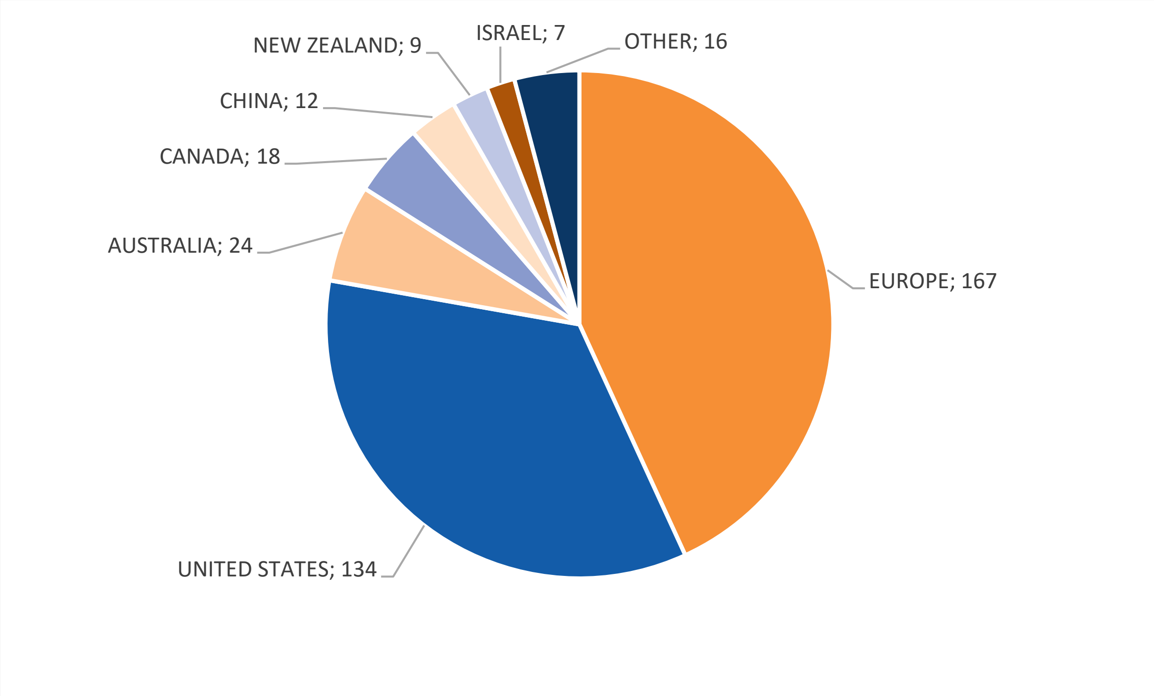


Figure 6: Countries of origin of the studies selected for inclusion in the analysis

Table Table 31 shows the most popular exposure approaches and variable numbers found in stydies included in the measure synopses. As expected, before-after comparison studies are very frequently considered. When all meta-analysis types are considered together, they comprise a significant category with increased weight due to the nature of their sampling.

Table 31: Types of studies included across the measures

Type of study	Number of studies
Before-After	160
Quasi-Experimental	64
Observational	52
Cross-Sectional	46
Empirical Bayes	32
Meta-analysis (Random effects)	21
Simulation	20
Meta-analysis (Fixed effects)	18
Case-Control	17
Experimental	17
Crossover/Repeated Measures	9
Full Bayes	7
Meta-analysis	7
Matched	5
Randomized	2
Time-Series	2
Cohort	1
Intervention Modelling	1
Unmatched	1

Furthermore, as shown on **Table 32**, most measures were investigated with a single exposure variable, but there were numerous cases where more than one variables were examined instead. A common example is behavioural approaches examining driver-related variables such as speed variations, lateral position and eye movement.

Table 32: Number of exposure variables per measure

Number of exposure variables per Measure	Number of Measures
1	44
2	7
3	10
4	9
5	10
>5	10

Table 33 shows the most examined outcomes in measure studies. It is evident that more traditional road safety variables were present in the studies such as those examining road accidents, injuries or road user behaviour.

Table 33: Types of outcomes across the risk factors

Type of Outcome	Number of Risk Factors
Accident rate/risk	96
Vehicle speed	58
Behaviour of drivers/pedestrians	52
Injury or Casualty rate/risk	38
Conflicts	5
CMF	4
Other	3

Table 34 provides an overview of the coded studies per taxonomy topic (i.e. measure) and the total number of effects analysed for the topics where a synopsis was written. The number of effects are a result of the approach that each researcher adopts. For instance, a study producing a model relating a measure to crashes might produce fewer effects than a study comparing different age groups for descriptive statistics (regardless of sample of both studies).

Table 34: Number of studies and effects per synopses for measures

Infrastructure Element	Specific Measure	No. of studies*	Total no. of effects
Exposure	2+1 roads	2	12
	HGV traffic restrictions	4	18
Infrastructure safety management	Road safety audits & inspections	5	67
	High risk sites treatment	4	30
	Speed limit reduction measures to increase road safety	5	9
	Dynamic speed limits	5	12
	Dynamic speed display signs	5	12
	Installation of section control & speed cameras	8	27
	Installation of speed humps	6	19
	Implementation of woonerfs	5	28
	Implementation of narrowings	4	60
	School zones	8	23
	Implementation of 30-zones	5	40
	Traffic calming schemes	4	20
	Creation of by-pass road	4	12
Road surface	Road surface treatments	6	6
Lighting	Installation of lighting & Improvement of existing lighting	4	26
Workzones	Workzones: Signage installation and improvement	5	79
Cross-section - Road segments	Increase number of lanes	5	8
	Increase lane width	6	17
	Installation of median	1	14
	Increase median width	2	32
	Change median type	1	18
	Implementation of rumble strips at centreline	1	4
	Shoulder implementation (shoulder type)	3	56
	Increase shoulder width	6	134
	Change shoulder type	2	84
	Safety barriers installation; Change type of safety barriers	7	166
	Create clear-zone / remove obstacles & Increase width of clear-zone	1	2
	Road markings implementation	8	124
	Installation of chevron signs	7	150
	Implementation of edgeline rumble strips	5	49
	Installation of cycle lane and cycle path	3	15
	Traffic sign installation; Traffic sign maintenance	5	67
Traffic control - Road segments	Variable message signs	5	66
	V2I schemes	4	14
	Convert at-grade junction to interchange	3	15
Alignment-junctions	Channelisation	11	28

Infrastructure Element	Specific Measure	No. of studies*	Total no. of effects
	Sight distance treatments	9	23
	Convert junction to roundabout - overall	17	29
	Convert 4-leg junction to staggered junction	4	15
	Improve skewness or junction angle	3	7
	Installation of rail-road crossing traffic sign	6	40
Traffic control - junctions	Automatic barriers installation	8	24
	STOP / YIELD signs installation / replacement	7	20
	Implementation of marked crosswalk	7	16
	Traffic signal installation	6	29
	Traffic signal reconfiguration	8	65
Total		**250**	**1831**

Finally, the effects reported on **Table 34** were further analysed with regards to their impacts on road safety (positive/unclear/negative). **Figure 8** summarizes the results, from which an overall idea for each measure can be obtained. More detailed information, such as the effects of meta-analyses (which have increased weight) or differences across road user groups have to be obtained from each individual synopsis, however. Therefore, the colour code assignment was done after taking this detailed information into account for each synopsis. As expected, measures have a mostly positive impact on road safety overall when viewed collectively.

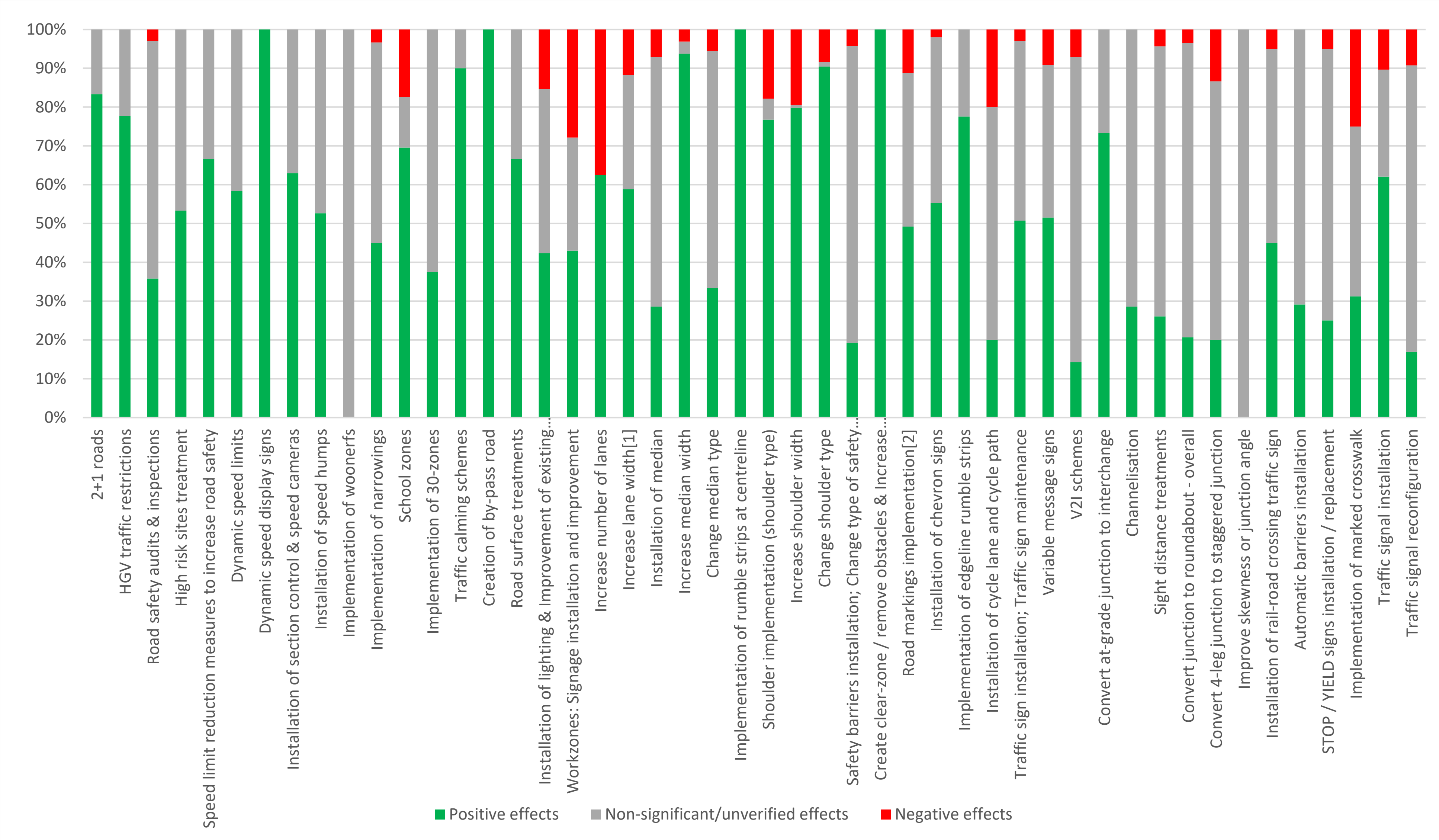


Figure 7: Measure studies effects distribution

4.3.1 Specific examples of analysis of coded studies per topic

As an indicative example, tables summarising coded studies are presented from two synopses: Traffic signal installation (**Table 35**) and HGV Traffic Restrictions (**Table 36**). The format followed includes (i) qualitative description tables that summarize study design and main results and (ii) quantitative tables evaluating specific effects and impacts on road safety.

Table 35: Traffic signal installation – Description of coded studies

Number	Author(s); Year; Country;	Sampling frame for signal installation studies	Method for signal installation investigation	Outcome indicator	Main Result
1	**Elvik, R., Høye, A.; 2015; Norway [meta-analysis]**	Summary of effects that can be expected from traffic signal installation from previous research.	Crash comparison [Random effects meta-analysis]	Crash comparison [Percentage difference]	The total number of accidents is reduced by 29 % after installing traffic signals, many additional results.
2	**Elvik, R., Høye, A.; 2015; Norway [meta-analysis]**	Summary of effects that can be expected for implementation of specific measures related to left turn phasefrom previous research.	Crash comparison [Random effects meta-analysis]	Crash comparison [Percentage difference]	Both a protected left-turn phase and a protected-permissive left-turn phase have no effect when all crashes are considered. Both measures reduce person damage injuries in crashes that occur when turning left by 14-15%.
3	**Celik, A. K., & Oktay, E.; 2014; Turkey**	A retrospective cross-sectional study is conducted analysing 11,771 traffic accidents reported by the police in two provinces of Turkey.	Comparison between injury type categories [Multinomial logit model]	Injury category comparison [Odds ratio - Slope]	The estimation results showed that some traffic control devices are not sufficiently able to decrease fatal injuries.
4	**Gitelman, V., Hakkert, A. S., Doveh, E., & Cohen, A.; 2001; Israel**	Data on road infrastructure and some 400 interurban and some 500 urban projects were recorded in the database from which more than 30 examples of treatment types evolved.	Crash comparison [Before - after analyses]	Injury crashes comparison [Odds ratio - Percentage difference]	Significant injurious crash reductions were observed (20-21%).
5	**Persaud, B., Council, F., Lyon, C., Eccles, K., & Griffith, M.; 2005; United States**	Study methodology included collection of background information and specification of statistical methodology. Afterwards 132 sites with red light cameras in the US were examined.	Crash comparison [Empirical Bayes and before - after analyses]	Crash comparison [Percentage difference]	Results showed a significant decrease in right-angle crashes but a significant increase in rear-end crashes.
6	**Sacchi, E., Sayed, T., & El-Basyouny, K.; 2016; Canada**	The countermeasure analysed was the installation of traffic signals at unsignalised urban/suburban intersections in British Columbia	Crash comparison [Full Bayes and before - after analyses]	Crash comparison (annual and predicted) [Absolute & Percentage difference, CMF]	Results showed that traffic signal treatments led to reductions of collision frequency. These reductions were more marked for severe than non-severe crashes.

Table 36. Traffic signal installation – Quantitative results of coded studies and impacts on road safety

Number	Author(s); Year; Country	Measure Exposure	Outcome indicator	Quantitative Estimate	Effect on road safety
1	**Elvik, R., Høye, A.; 2015; Norway [meta-analysis]**	Installation of traffic signals	Crash comparison [Percentage difference]	Accident collisions - Total: Percent change = -29.00%, CI [95%] = (-41.00%, -14.00%)	↑
				Accident collisions - With crossing vehicle: Percent change = -74.00%, CI [95%] = (-77.00%, -71.00%)	↑
				Accident collisions - Left-turn: Percent change = -60.00%, CI [95%] = (-65.00%, -54.00%)	↑
				Accident collisions - Rear-end: Percent change = 45.00%, CI [95%] = (24.00%, 70.00%)	↓
2	**Elvik, R., Høye, A.; 2015; Norway [meta-analysis]**	Implementation of left-turn phase	Crash comparison [Percentage difference]	Accident collisions - Total: Accident severities - All All accident types Percent change = 0.00%, CI [95%] = (-9.00%, 9.00%)	-
				Accident collisions - Total: Accident severities - Injury Accidents by turning or crossing into a road Percent change = -15.00%, CI [95%] = (-19.00%, -12.00%)	↑
				Accident collisions - Total: Accident severities - All Accidents by turning or crossing into a road Percent change = 3.00%, CI [95%] = (-1.00%, 8.00%)	-
				Accident collisions - Total: Accident severities - All Accidents when turning left Percent change = -14.00%, CI [95%] = (-21.00%, -5.00%)	↑
				Accident collisions - Total: Accident severities - All Accidents - rear end Percent change = 8.00%, CI [95%] = (0.00%, 15.00%)	-
3	**Celik, A. K., & Oktay, E.; 2014; Turkey**	Installation of traffic signals	Injury category comparison [Odds ratio]	Injury/Fatality Odds ratio: OR = 4.030, t-test = 3.05, p = 0.05, CI [95%] = (1.650, 9.870)	↑
			Injury category comparison [Slope]	No Injury/Fatality Slope: b = 5.670, t-test = 3.80, p = 0.05, CI [95%] = (2.320, 13.900)	↑
4	**Gitelman, V., Hakkert, A. S., Doveh, E., & Cohen, A.; 2001; Israel**	Installation of traffic signals	Injury crashes comparison [Percentage difference]	Injury crashes, All areas Percent change = -20.00%	↑
				Injury crashes, Urban areas Percent change = -21.00%	↑
			Injury crashes comparison [Odds ratio]	Injury crashes, Urban areas [With reference group] OR = 0.7920, CI [95%] = (0.6080, 1.0330)	↑
				Injury crashes, Urban areas [Without reference group] OR = 0.6950, CI [95%] = (0.5750, 0.8400)	↑
5	**Persaud, B., Council, F., Lyon, C., Eccles, K., & Griffith, M.; 2005; United**	Installation of Red Light Camera systems	Crash comparison [Percentage difference]	Accident severities - All Accidents - Right angle Percent change = -24.60%, s.e. = 2.900	↑

Number	Author(s); Year; Country	Measure Exposure	Outcome indicator	Quantitative Estimate	Effect on road safety
	States			Accident severities - Injury Accidents - Right angle Percent change = -15.70%, s.e. = 5.900	↑
				Accident severities - All Accidents - Rear-end Percent change = 14.90%, s.e. = 3.000	↓
				Accident severities - Injury Accidents - Rear-end Percent change = 24.00%, s.e. = 11.600	↓
6	**Sacchi, E., Sayed, T., & El-Basyouny, K.; 2016; Canada**	Installation of traffic signals	Crash comparison [Relative difference]	Accident sites - All Accident severities - Fatal plus Injury Relative difference of Annual average collision frequency = -0.4200	-
				Accident sites - All Accident severities - Damage only Relative difference of Annual average collision frequency = 3.3300	-
				Accident sites - Treatment only Accident severities - Fatal plus Injury Relative difference of Annual average collision frequency = 0.5500	-
				Accident sites - Treatment only Accident severities - Damage only Relative difference of Annual average collision frequency = 1.4200	-
			Crash comparison [CMF]	Accident sites - All Accident severities - All CMF [before - after] = 0.8400, p<0.05	↑
				Accident sites - All Accident severities - Fatal plus Injury CMF [before - after] = 0.7820, p<0.05	↑
				Accident sites - All Accident severities - Damage only CMF [before - after] = 0.8980, p<0.05	-
			Predicted Crash comparison [Percentage difference]	Accident sites - All Accident severities - All Prediction difference = 16.00	↑
				Accident sites - All Accident severities - Fatal plus Injury Prediction difference = 21.80	↑
				Accident sites - All Accident severities - Damage only Prediction difference = 10.20	↑
↑	**denotes positive road safety effects**		**-**	**denotes unclear or marginal road safety effects**	
↓	**denotes negative road safety effects**		*** denotes that no statistical analysis was conducted for the significance of the effects**		

4.4 ROAD SAFETY MEASURES SYNOPSES

Ultimately **48 synopses on road infrastructure measures** have been developed for inclusion in the DSS. The vast majority of them include results of **existing meta-analyses**, and two of them include results of **new meta-analyses** carried out within SafetyCube (road safety audits & inspections, and increasing shoulder width). This has been accomplished by 9 different SafetyCube partner organisations. It has to be noted that due to available studies and some contents of the synopses their titles were slightly adapted by the authors in certain cases. The results are presented in the following.

Furthermore, it should be underlined that the synopses included in this Deliverable are the **final versions available at the time of the submission**, which have been thoroughly reviewed within the WP, and also within the project (Deliverables internal review procedures). Nevertheless, **the synopses are living documents**, which may be further improved also after the Deliverable submission (e.g. if new studies are identified, if additional suggestions for improvement are received by project partners). Moreover, a thorough Quality Assurance procedure is being implemented for all the contents of the DSS before the end of the project. Therefore, any further improvements in the synopses included in this Deliverable will be reflected in the **final versions available in the DSS at the end of the project**.

In addition to the above, for the following sets of topics (n=29 measures) a single combined synopsis was produced, mostly due to the form of studies found from the international literature or high affinity of topics:

- Formal tools to address road network deficiencies / Road safety audits implementation & Road safety inspections implementation
- Speed management & enforcement / Speed cameras & Section control
- Road surface treatments / Improve friction (type of surface) & Road re-surfacing to improve evenness & Ice prevention / winter maintenance
- Visibility / Lighting treatments / Installation of road lighting & Improvement of existing lighting
- Workzones / Workzone signage installation & Workzone signage improvement
- Shoulder & roadside treatments / Safety barriers installation & Change type of safety barriers
- Shoulder & roadside treatments / Create clear-zone / remove obstacles & Increase width of clear-zone
- Cycle lanes / Cycle lane treatments & Cycle path treatments
- Traffic signs treatments / Traffic sign installation & Traffic sign maintenance
- Driver information and alert / Variable message signs: incident / accident warning & Variable message signs: congestion / queue warning
- Traffic signs treatments / STOP / YIELD signs installation & STOP / YIELD signs replacement
- Traffic signals treatments / Improve traffic signals timing & Implementation of pedestrian signal phase
- Delineation and road marking / Road markings implementation & Road markings / Road markings implementation
- Lanes / ramps treatments / Increase lane width & Interchanges treatments / Increasing lane width

Table 37 presents the measures synopses respectively separated by colour code. In total:

- 16 measures were given the colour **Green, indicating that there is consistent evidence** that they have a positive effect on road safety in terms of decreasing crash risk, frequency or severity.
- 19 measures were marked as light green (probably effective) with a likely positive effect on road safety.
- Grey (unclear) was assigned to 14 treatments, where no clear conclusion could be drawn.

Table 37: Infrastructure related measure synopses by colour code

Green (clearly reducing risk)	Light green (probably reducing risk)	Grey (Unclear)
✓ **HGV traffic restrictions** ✓ **Speed limit reduction measures to increase road safety** ✓ **Dynamic speed display signs** ✓ **Installation of section control & speed cameras** ✓ **Installation of speed humps** ✓ **Implementation of 30-zones** ✓ **Installation of lighting & Improvement of existing lighting** ✓ **Workzones: Signage installation and improvement** ✓ **Implementation of rumble strips at centreline** ✓ **Installation of chevron signs** ✓ **Traffic sign installation; Traffic sign maintenance** ✓ **Convert at-grade junction to interchange** ✓ **Sight distance treatments** ✓ **Automatic barriers installation** ✓ **Dynamic speed limits** ✓ **Creation of by-pass roads**	✓ Road safety audits & inspections ✓ High risk sites treatment ✓ Implementation of narrowings ✓ School zones ✓ Installation of traffic calming schemes ✓ Road surface treatments ✓ Increase median width ✓ Change median type ✓ Shoulder implementation (shoulder type) ✓ Increase shoulder width ✓ Safety barriers installation; Change type of safety barriers ✓ Create clear-zone / remove obstacles & Increase width of clear-zone ✓ Implementation of edgeline rumble strips ✓ Variable message signs ✓ <u>Convert junction to roundabout</u> ✓ Channelisation ✓ Installation of rail-road crossing traffic sign ✓ Traffic signal installation ✓ 2+1 roads	? Implementation of woonerfs ? Installation of median ? Increase number of lanes ? Increase lane width ? Change shoulder type ? Installation of cycle lane and cycle path ? V2I schemes ? <u>Convert junction to roundabout (cyclists)</u> ? Improve skewness or junction angle ? Convert 4-leg junction to staggered junctions ? STOP / YIELD signs installation / replacement ? Road markings implementation ? Implementation of marked crosswalk ? Traffic signal reconfiguration

*The measures which are <u>underlined</u> have more than one colour code, but for different road user types.

A detailed overview of the infrastructure related road safety topics is presented in Table 38. Results are separated for each of the infrastructure element, with the specific measures within each element **ranked by colour code and indication on the type of road safety outcomes affected, as well as whether or not this is a hot topic**. Moreover, the road category which they are applied to is noted, and any conditions under which the road safety effect might change from the baseline are included in the 'Additional Remarks' field.

Furthermore, the topics for which a synopsis could not be produced are reported as well (n=31), together with the respective explanation. This was predominantly due to the lack of enough relevant studies, measure oriented or in general. However, any studies that were found were coded and are available in the DSS (yet without a synopsis).

Table 38: Overview of results on infrastructure related measures and associated impact on crashes

Infrastructure Element	Specific Measure	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied: Motorways	Road types studied: Rural Roads	Road types studied: Urban Roads	Additional Remarks
Exposure	2+1 roads	Light green	-	-	↓	N		✓		The effect of 2+1 roads without median barrier is not clear.
	HGV traffic restrictions	Green	↓	↓	-	N	✓	✓		
	Flow diversion	**N/A**	No relevant studies could be found							
	Reversible lanes	**N/A**	Only the meta-analysis from the Handbook of Road Safety Measures was found							
	One-way traffic	**N/A**	Only the meta-analysis from the Handbook of Road Safety Measures was found							
	Ramp metering	**N/A**	Not enough relevant studies could be found							
	Access control	**N/A**	Only one measure study was found; a risk synopsis was created: "Absence of access control"							
	Creation of HGV lanes	**N/A**	No relevant studies could be found							
Infrastructure safety management	Road safety audits & inspections	Light green	↓	↓	-	N	✓	✓	✓	
	High risk sites treatment	Light green	↓	↓	-	N	✓	✓	✓	
	Land use regulations improvement	**N/A**	No relevant studies could be found							
	Speed limit reduction measures to increase road safety	Green	↓	↓	-	N	✓	✓	✓	Due to the exponential link of speed and crash risk/injury severity, the measure appears more effective in higher speed limits (highways).
	Dynamic speed limits	Green	↓	↓	-	Y	✓			Overall effectiveness varies with driver compliance levels.
	Dynamic speed display signs	Green	-	↓	-	Y	✓	✓	✓	DSDSs that extend the numeric feedback with verbal messages tend to outperform the ones with only numeric feedback.
	Installation of section control & speed cameras	Green	↓	↓	-	N	✓ (section control)	✓ (speed cameras)	✓ (speed cameras)	

Infrastructure Element	Specific Measure	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional Remarks
							Motorways	Rural Roads	Urban Roads	
	Installation of speed humps	Green	↓	↓	-	N			✓	
	Implementation of woonerfs	Grey	-	-	-	N			✓	
	Implementation of narrowings	Light green	↓	-	-	N			✓	
	School zones	Light green	↓	-	-	N			✓	
	Implementation of 30-zones	Green	↓	↓	-	N			✓	30km/h zones only work effectively if physical speed reducing measures are implemented alongside the reduced speed limit.
	Traffic calming schemes	Light green	↓	↓	-	N			✓	Significant results were also found for specific groups of accidents or casualty types (e.g., drivers over 25, single vehicle crashes, local/main roads), but not for others (e.g., pedestrian crashes, fatal casualties, drivers under 25 years).
	Creation of by-pass roads	Green	-	↓	-	N			✓	Safety effects of bypass roads are expected to be larger when the old road through town has a larger accident rate, more traffic is shifted to the bypass road, no extra traffic to either the old or the new road is generated, speed-reducing measures are used to control for possible increases in speeding on the old road network, and when intersections between the old and new bypass road have a safer design.
Road type	Upgrade / downgrade road class	**N/A**	No relevant studies could be found							

Infrastructure Element	Specific Measure	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional Remarks
							Motorways	Rural Roads	Urban Roads	
	Upgrade road to motorway	**N/A**	No relevant studies could be found							
Road surface	Road surface treatments	Light green	-	↓	-	N	✓	✓	✓	
Lighting	Installation of lighting & Improvement of existing lighting	**Green**	-	↓	↓	Y	✓	✓	✓	Effects are generally larger for fatal crashes than for less severe crashes, and more favourable for crashes involving pedestrians than for other types of crashes.
Workzones	Workzones: Signage installation and improvement	**Green**	↓	-	-	Y	✓	✓	✓	Decreases in speed limit compliance rates farther from the workzone site.
	Workzone length treatment	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							
	Workzone duration decrease	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							
Alignment - Road segments	Creation of weaving area	**N/A**	No relevant studies could be found							
	Increase horizontal curve radius (curve re-alignment)	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							
	Implement transition curves (curve re-alignment)	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							
	Reduce number of curves (re-alignment)	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							
	Reduce tangent length	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							
	Sight distance treatments (horizontal	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							

Infrastructure Element	Specific Measure	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied: Motorways	Road types studied: Rural Roads	Road types studied: Urban Roads	Additional Remarks
	alignment)									
	Reduce gradient (re-alignment)	**N/A**	No relevant studies could be found							
	Increase vertical curve radius (curve re-alignment)	**N/A**	No relevant studies could be found							
	Sight distance treatments (vertical alignment)	**N/A**	No relevant studies could be found							
	Superelevation improvement	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							
	Cross-slope improvement	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							
Cross-section - Road segments	Increase number of lanes	Grey	-	-	-	N	✓	✓	✓	
	Increase lane width[7]	Grey	-	-	-	N	✓	✓	✓	On two-lane rural or urban roads the widening of lanes tends to improve road safety. For rural two-lane highway roads there is robust evidence that increasing lane width reduces the occurrence of single vehicle run-off-road same and opposite direction crashes. At the same time studies have indicated that very wide lanes (or shoulders) may increase crash risk mainly due to higher speeds
	Create speed change lane	**N/A**	No relevant studies could be found							

[7] This synopsis contains two similar topics: Cross-section – Lanes / ramps treatments / Increase lane width & Interchanges treatments / Increasing lane width

Infrastructure Element	Specific Measure	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional Remarks
							Motorways	Rural Roads	Urban Roads	
	Installation of median	Grey	-	-	↓	N		✓	✓	Installation of medians reduces the number of accidents on road segments, with the greatest effect on the most severe accidents. The effect is greatest on control-access roads like motorways (roads with no at grade intersections). Installation of medians at intersections are found to increase accidents. Unfavourable effects of median installation have been found in curves and when medians imply narrower lanes.
	Increase median width	Light green	↓	↓	-	N	✓	✓	✓	The effect in intersections is larger, but not statistically significant. Intersections with wide medians (wider than 2 m) have more accidents than intersections with medians lower than 2 meters. Increasing the median width appears to reduce the number of car accidents as well as the number of bicycle accidents at two way roads on urban and rural roads.
	Change median type	Light green	↓	↓	-	N	✓	✓	✓	
	Implementation of rumble strips at centreline	Green	↓	↓	-	N	✓	✓		

Infrastructure Element	Specific Measure	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional Remarks
							Motorways	Rural Roads	Urban Roads	
	Shoulder implementation (shoulder type)	Light green	↓	↓	-	Y	✓	✓		A higher positive effect is observed for horizontal curve segments than for tangent road segments. Shoulder implementation was negatively effective for fatal accidents on rural and urban two-lane roads, injury accidents on rural interstate roadways, injury and property damage only accidents on rural multilane roads with a shoulder width of 2.4 m.
	Increase shoulder width	Light green	↓	-	-	Y	✓	✓		
	Change shoulder type	Grey	-	-	-	N	✓	✓		
	Safety barriers installation; Change type of safety barriers	Light green	-	↓	↓	Y	✓	✓		
	Create clear-zone / remove obstacles & Increase width of clear-zone	Light green	↓	↓	-	Y		✓	✓	
	Removal of sight obstructions	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							
	Road markings implementation[8]	Grey	-	-	-	N	✓	✓	✓	
	Installation of chevron signs	**Green**	↓	↓	-	N	✓	✓		
	Implementation of edgeline rumble strips	Light green	↓	↓	-	N	✓	✓		

[8] This synopsis contains two similar topics: Cross-section – Road segments / Road markings implementation & Traffic-control – junctions / Road markings implementation

Infrastructure Element	Specific Measure	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional Remarks
							Motorways	Rural Roads	Urban Roads	
	Transverse rumble strips	**N/A**	Only few studies could be found; no synopsis produced							
	Sidewalk installation	**N/A**	No relevant studies could be found							
	Increase of sidewalk width	**N/A**	No relevant studies could be found							
	Installation of cycle lane and cycle path	Grey	-	-	-	N			✓	The implementation of cycle tracks has a non-significant effect in reducing collisions between cyclists and motor vehicles and may increase the total number of accidents, particularly road accidents at intersections.
	Traffic sign installation; Traffic sign maintenance	Green	↓	-	-	Y	✓	✓	✓	
Traffic control - Road segments	Variable message signs	Light green	↓	↓	↓	Y	✓	✓	✓	
	V2I schemes	Grey	↓	-	-	N	✓	✓	✓	
	Convert at-grade junction to interchange	Green	↓	↓	-	N		✓	✓	
	Increasing ramp width	**N/A**	No relevant studies could be found							
	Increasing ramp curve radius (ramp re-alignment)	**N/A**	No relevant studies could be found							
	Increasing acceleration / deceleration lane length	**N/A**	Mainly risk related studies could be identified, hence the risk synopsis was updated							

Infrastructure Element	Specific Measure	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional Remarks
							Motorways	Rural Roads	Urban Roads	
Alignment-junctions	Channelisation	Light green	↓	↓	-	N		✓	✓	Differences between the effectiveness of left-turn lanes and of right-turn lanes or between T-arms and crossroads are different to quantify
	Sight distance treatments	Green	↓	↓	-	Y		✓	✓	
	Convert junction to roundabout - overall***	Light green	-	↓	↓	N		✓	✓	In the case of multi-lane roundabouts, there can even be increases to damage only accident frequency. Roundabouts are also more effective on roads with a higher speed limit.
	Convert junction to roundabout - cyclists***	Grey	-	↑	-	N		✓	✓	
	Convert 4-leg junction to staggered junction	Grey	-	-	-	N		✓	✓	Converting 4-leg junctions to staggered T-junctions when the amount of side road traffic is low, appears to significantly increase injury as well as property damage only crash occurrence
	Improve skewness or junction angle	Grey	-	-	-	Y		✓	✓	
	Installation of rail-road crossing traffic sign	Light green	↓	↓	-	N		✓	✓	Stop signs were negatively effective at crossings with higher train speeds (e.g. train speed higher than 30 mph) or track classifications (classes mainly referring to the maximum speed limit). Other types of specific warning signs (e.g. hazard warning signs or highly reflective warning signs) seem to significantly reduce crash occurrence as well.
Traffic control -	Automatic barriers installation	Green	↓	↓	-	N		✓	✓	

Infrastructure Element	Specific Measure	Colour code	Crash risk*	Crash frequency	Crash severity**	Hot topic (Yes/No)	Road types studied			Additional Remarks
							Motorways	Rural Roads	Urban Roads	
junctions	STOP / YIELD signs installation / replacement	Grey	-	-	-	N		✓	✓	Only the installation of two-way stops and four-way stops significantly reduces crash occurrence. For the installation of one-way stops only non-significant results were presented. This applies also for installing yield signs. The replacement of stop signs by yield signs, however, seems to significantly increase crash occurrence.
	Implementation of marked crosswalks	Grey	-	-	↓	N		✓	✓	Most results refer to crosswalks at intersections, only few refer to crashes at midblock crosswalks.
	Traffic signal installation	Light green	↓	↓	↓	N		✓	✓	Overall, crash occurrence and severity are mitigated, although one specific crash type increased after the installation, which was rear-end crashes.
	Traffic signal reconfiguration	Grey	-	-	-	N		✓	✓	

* Crash risk –number of crashes per unit of exposure.
** Crash severity – the severity of the injuries sustained by the casualties involved in the crashes
***These measures have more than one colour code, but for different road user types.

When reviewing the results overall, it appears that road safety measures appear to be more focused in their applications regarding road types compared to risk factors. Out of the 48 road safety measures analysed in total, only 16 can be claimed to apply across motorways, rural and urban roads, and they are usually relevant to general road elements such as traffic signs (installation; maintenance) or road pavement (surface treatments).

Moreover, 14 measures were found to be implemented on both rural and urban roads, and these were largely measures concerning junctions (for instance signal measures or junction geometry reconfiguration measures). Furthermore, 8 measures concerned motorways and rural roads, and these were relevant to geometry elements that isolate traffic (such as shoulder measures and barrier installation), which are not typically found in an urban environment. Respectively, 8 road safety measures concerning elements of urban environments are implemented exclusively on urban roads (speed humps, traffic calming schemes, 30-zones etc.). Lastly, only one measure concerned motorways only (dynamic speed limits) and only one measure concerned rural roads only (2+1 roads).

Without considering the other road categories each time, 25 measures can be applied to motorways, 39 to rural roads and 38 to urban roads.

4.5 COST-BENEFIT ANALYSES

A cost-benefit analysis (CBA) allows the joint evaluation of the effectiveness of measures in reducing crashes of different severity and to provide information on the socio-economic return of countermeasures. Therefore a monetary value is assigned to each type of benefit that results from the measure. The sum of these monetary values is compared to costs of the measure. In a CBA two statistics can be calculated:

(1) the net present value (NPV) = Benefits – Costs
(2) the benefit-to-cost ratio (BCR) = Benefits / Costs.

If the benefits are greater than the costs, a measure is cost-effective. For the NPV this means a value higher than 0 and for the BCR this means a value higher than 1. Measures can be ranked or prioritized based on the NPV or BCR. The CBA methodology and tools used (E3 Calculator) are presented in Chapter 2.2.4 of this report.

From all the measures defined and examined in this research, it was decided to conduct a cost-benefit analysis to those that were found at least somewhat effective in improving road safety and were thus assigned **a "light green" or "green" colour code**. **Table 39** summarizes the results of these analyses and includes NPVs and BCRs of the measures. All NPVs are calculated per unit of analysis in order to enable a proper comparison. In case of a BCR below 1 the NPV becomes negative by definition as the estimated costs exceed the benefits. All negative NPVs are indicated in red.

Table 39: B/C ratios and Net Present Values per unit for all the selected measures

Measure	Unit of analysis	Benefit-to-cost ratio (best estimate)	Net Present Value (in EUR EU-2015 PPP)	Total costs per unit of analysis (in EUR EU-2015 PPP)	Break-even measure cost (in EUR EU-2015 PPP)
Road safety audits - Light measure case	1 km	21.7	€ 1 641 482	€ 79 189	€ 1 720 671
Road safety audits - Heavy measure case	1 km	2.9	€ 1 121 380	€ 599 291	€ 1 720 671
High risk sites treatment	1 location (intersection)	16.1	€ 869 803	€ 57 561	€ 927 363
Dynamic speed limits	1 km	1.1	€ 31 548	€ 490 192	€ 521 739
Section control	1 km	19.5	€ 2 834 895	€ 152 913	€ 2 987 808
Installation of speed humps	1 area	18.2	€ 3 234 711	€ 187 953	€ 3 422665
Implementation of 30-zones	1 area	1.6	€ 66 038[9]	€ 110 226	€ 176 265[1]
Installation of lighting & Improvement of existing lighting	1 km	0.7	€ -24 888	€ 85962	€ 61073
Implementation of rumble strips at centreline	1 km	9.1	€ 7950	€ 987	€ 8938
Installation of chevron signs	1 location (curve)	2.7	€ 875	€ 504	€ 1379
Channelisation	1 location (intersection)	8.4	€ 1 452 858	€ 196 061	€ 1 648 919
Automatic barriers installation	1 location (level crossing)	0.05	-€ 197 399	€ 208 698	€ 11 299
Installation of traffic calming schemes	1 area	0.4	-€ 392 061	€ 612 633	€ 220 572
Installation of traffic calming schemes (b)	1 area	0.2	-€ 4 199 122	€ 5 389 225	€ 1 190 103
Road surface treatments	1 location (intersection)				€ 1 123 604
Winter maintenance	1 km	6.0	€ 2 609	€ 519	€ 3128
Safety barriers installation	1 km	19.5	€ 1 339 933	€ 72 314	€ 1 412 247
Convert junction to roundabout	1 location (intersection)	9.2	€ 3 749 171	€ 455 122	€ 4 204 293

[9] Converted from the obtained NPV (60 035) and break-even cost (160 241) in GBP to EUR by applying the PPP-conversion factor of 1.1 (see Martensen et al, 2016).

Traffic signal installation- rural roads	1 location (intersection)	1.1	€ 8731	€ 98 285	€ 107 016
Traffic signal installation - highways	1 location (intersection)	3.7	€ 559 388	€ 206 874	€ 766 263

The results of any cost-benefit analysis are much dependent on the underlying assumptions about the effect of the concerned measure. However, effect estimates are – even in the best known cases – only known within a certain uncertainty margin. It is therefore useful to run a **sensitivity analysis** based on some alternative assumptions about the effects of the measure. The purpose is to show to which extent benefit-to-cost ratios are sensitive to changes in the underlying effect estimates. For the vast majority of the CBA sensitivity analyses that use some alternative effect estimates were conducted.

If available **the upper and lower limits of the 95% confidence intervals of the estimates** were used. In the ideal case these estimates were resulting from a meta-analysis, in other cases the used values result from one or two particular studies. The used values represent a (much) lower than expected and a (much) higher than expected effect respectively.

Further to that, in order to reflect the inherent uncertainty of cost estimates it was decided to also include two scenarios in which **the measure costs vary from a 'very low' (-50% of the estimate) level to a 'very high' (+ 100% of the best estimate) level**. These threshold values are to a certain extent arbitrary, but they are believed to reflect realistic boundaries.

Finally two rather extreme scenarios were defined:

- **a 'worst case' scenario** as a combination of a much worse than expected effect (in principle the lower limit of the 95% confidence interval of the effect estimate) and a higher than expected measure cost (i.e. the estimated cost +100%).
- **an 'ideal case' scenario** that is a combination of a much better than expected effect (upper limit of the 95% CI of the effect estimate) and a lower than expected measure cost (estimated cost -50%).

Results are presented collectively on **Table 40** which follows.

Table 40: BCRs in all 7 scenarios with varying effect estimates

Measure	BCR						
	best estimate	low measure effect	high measure effect	low measure cost: -50%	high measure cost: +100%	worst case scenario = high cost + low effect	best case scenario = low cost + high effect
Road safety audits - Light measure case	21.7	16.4	27	43.5	10.9	8.2	54
Road safety audits - Heavy measure case	2.9	2.2	3.6	5.7	1.4	1.1	7.1
High risk sites treatment	16.1	13.2	18.4	32.2	8.1	6.6	36.8
Dynamic speed limits	1.1	-2.3	3.6	2.1	0.5	-1.2	7.2
Section control	19.5	14.7	23	39.1	9.8	7.3	46.1
Installation of speed humps	18.2	8.6	26.8	36.4	9.1	4.3	53.8
Implementation of 30-zones	1.6	0.6	2.5	3.2	0.8	0.3	5.1
Installation of lighting & Improvement of existing lighting	0.7	0.5	0.9	1.4	0.4	0.3	1.8
Implementation of rumble strips at centreline	9.1	7.6	10.3	18.1	4.5	3.8	20.5
Installation of chevron signs	2.7	1.4	5.5	5.5	1.4	0.7	10.9
Channelisation	8.4	1.2	14	16.8	4.2	0.6	28
Automatic barriers installation	0.05	0.04	0.06	0.11	0.03	0.02	0.12
Installation of traffic calming schemes	0.4	0.3	0.4	0.7	0.2	0.1	0.8
Installation of traffic calming schemes (b)	0.2	-	-	-	-	-	-
Road surface treatments	-	-	-	-	-	-	-
Winter maintenance	6	-	-	12.1	3	-	-
Safety barriers installation	19.5	10.6	25.4	39.1	9.8	5.3	21.2
Convert junction to roundabout	9.2	8.1	10.2	18.5	4.6	4	20.4
Traffic signal installation	1.1	0.5	1.5	2.2	0.5	0.3	3.1

4.6 MAIN RESULTS FROM EFFECTIVENESS AND EFFICIENCY EVALUATION

After the CBA results were assessed, the ranking and classification of the examined infrastructure measures was enabled based on the best estimate of their effectiveness (base BCR) and implementation costs per unit. The outcome is presented on **Table 41**.

Table 41: Cost-effectiveness classification of measures based on CBA results

		Costs (per unit)	
		Low [Costs < 100.000 €/unit]	High [Costs ≥ 100.000 €/unit]
Effectiveness	Low [BCR < 2.0]	Installation of chevron signs Traffic signal installation Installation of lighting & Improvement of existing lighting	Automatic barriers installation at rail-road crossings Installation of traffic calming schemes Installation of traffic calming schemes Dynamic speed limits Implementation of 30-zones
	High [BCR ≥ 2.0]	Road safety audits - Light measure case Winter maintenance Safety barriers installation High risk sites treatment Implementation of rumble strips at centreline	Road safety audits - Heavy measure case Traffic signal installation - highways Channelisation Convert junction to roundabout Section control Installation of speed humps

It is evident that, although all measures were selected on their basis of their proved effectiveness on crash reduction, some some of these measures are much more cost-effective than others (for instance winter maintenance compared to dynamic speed limits). Nevertheless, the perceived social costs and the particularities of each road safety intervention may justify its implementation even though it might not be the most cost-effective measure, such as in a scenario where only a less costly measure (such as chevron sign installation) is appropriate.

5 Main challenges addressed and limitations of the results

This chapter discusses the main challenges addressed within this work, as well as some methodological and data limitations that need to be taken into account when interpreting the results. Special mention is made to the results concerning the infrastructure "hot topics" indicated by infrastructure stakeholders.

5.1 "DUALITY" OF RISKS AND MEASURES

The high degree of duality between infrastructure risks and measures, mentioned in section 2.1, presents **methodological implications** as well.

Traditionally, the effects of risk factors are analysed by means of cross-sectional studies, while the effects of road safety measures / interventions are analysed by means of observational before-and-after studies (e.g. Empirical Bayes). During the infrastructure risks analyses, all studies found were indeed cross-sectional and yielded a risk estimate. However, during the measures analyses, it was identified at an early stage during the literature search that some topics from the measures taxonomy were only analysed in the literature through cross-sectional studies, and no relevant before-and-after studies could be found.

Examples of such measures were re-alignment treatments (curves, some elements of the cross-section), interchanges ramps and lanes engineering treatments, and workzones treatments. To a large extent, this is not surprising as, for instance, the implementation of "heavy" or extensive engineering treatments (total re-alignment of a road or a junction) is rare, and their documented examination within scientific papers even more so; respectively, workzones are part of a maintenance or treatment implementation, and are seldom subject to interventions on their characteristics. Moreover, most of these topics had already been analysed from the risk viewpoint (i.e. the absence of a treatment or a design feature may induce risks).

Therefore, a challenge within the task of identifying studies to be included in the inventory of studies on measures was **to distinguish between risk factors and measures**. For example, studies dealing with the absence of a safety barrier may be designed to:

- record the different safety levels of sites with or without safety barrier, quantifying the risk due to the absence of the safety barrier, or the risk induced by the presence of the safety barrier e.g. injury risk for motorcyclists. Such studies were considered within the risks analysis. The aim within the risk analysis was therefore to find studies that quantified risks on the basis of a **cross-sectional study design**.
- record e.g. crashes before and after the installation of a safety barrier. Although addressing a risk factor, these studies describe effects resulting from the treatment of a risk factor/application of a remedial measure. Such studies were coded and considered within the measures analysis at hand. In these cases, the aim was to find studies that provided an estimate of the effectiveness of a measure in reducing crash risk, frequency and/or severity **through a before-and-after study design**.

Overall, in order to address this issue, it was decided to take an approach fully complying with the basic principle that **risks are analysed through cross-sectional studies, and measures are analysed through before-and-after studies**.

While writting synopses, the following approach was taken:

- If for a topic both cross-sectional and before-and-after studies were found (e.g. skewness/junction angle):
    - a measure synopsis was written on the basis of before-and after studies
    - If an existing risk synopsis was available, it was revised to include the new cross-sectional studies found.
    - If a risk synopsis was not available, the related topic was added to the risks taxonomy and a new risk synopsis was written.
- If for a topic only cross-sectional studies were found, an existing risk synopsis was updated for the aspect of the measures (e.g. curve re-alignment, workzone length), or a new one was written as above (e.g. access control).

For topics with no before-after studies and therefore no synopses, a disclaimer was written to appear on the search results page of the DSS, explaining the reasons for the lack results, and guiding the user to consider the results of the related risk synopsis, with a word of caution that these may be an approximation of the corresponding effect of the measure.

5.2 DIFFERENT EFFECTS FOR DIFFERENT ROAD USERS

In seveal cases, the effects of infrastructure risks or measures were largely contradicting: there were studies indicating positive effects on road safety, and studies indicating negative effects on road safety. The effects may vary for different road networks (e.g. urban vs. rural), different countries or settings (e.g. industrialised vs. developing countries) or different groups of road users (e.g. pedestrians vs. car occupants). The latter case was given particular emphasis, as the SafetyCube DSS aims to explicitly address the road safety risks and measures of different road user groups.

In theory, all **risk factors and measures may vary for different road user groups** (or other elements), and accounting for all these variations would require a huge amount of resources. Within SafetyCube, the variations were taken into account in each risk factor or measure synopsis, and the colour code was assigned taking into account these aspects.

Where there was strong evidence of different effects of a risk factor for different road users, a distinct colour code was assigned for the different groups. This was pursued not only **on the basis of the presence of strong difference, but also on the possibility to substantiate this difference on the basis of sufficient number of studies**.

A representative example from the risks analysis concerns the **risk factor 'Traffic composition', in which the effect known as "safety-in-numbers"** was analysed. The literature review and study analysis findings confirmed that, an increase in the volume of cyclists and pedestrians is associated with a net increase in crashes (between cyclists/ pedestrians and motor vehicles), but this increase is less than would be expected for the proportional increase in volume, corresponding to lower risk for each individual road user. A meta-analysis estimated that a doubling of the volumes of pedestrians or cyclists would correspond to a 41 % increase in crashes (across road types and areas). This is in accordance with a "Safety-in-numbers" effect (more cyclists/ pedestrian corresponds to a lower crash risk for each cyclist/pedestrian) - and this a red colour code was assigned for these road users - but it remains unclear if the lower risk is *caused* by the higher numbers of pedestrians/cyclists. On the other hand, the effect of the share of heavy goods vehicles on road safety is unclear (few studies with mixed results) - and this a grey colour code was assigned- and no studies were found on the share of powered two wheelers or public transport.

From the measures analysis, the **conversion from junction to roundabout** was found to be associated with different effects for different road user groups, namely as regards cyclists. The conversion of junctions to roundabouts seems to reduce fatal and injury accident frequency. However, in some cases, only small reductions and even increases of damage only accident frequencies are seen for multi-lane roundabouts. For crashes involving cyclists, although earlier studies or studies from grey literature reported relatively pisitive effects, significant negative effects were found in recent high quality studies, hence, a light green colour code / red colour code (for cyclists) is assigned to roundabouts.

Overall, although there was evidence of different risks for different road users in several cases, a distinct color code was assigned only for a few ones, which were mentioned in Chapters 3 & 4.

5.3 COMBINED EFFECTS OF RISK FACTORS OR MEASURES

The **interrelations of road characteristics** can certainly not be ignored. In fact, several evaluation studies reported combined impacts of various risks or measures, e.g. a simultaneous change of lanes and shoulders; adding a lane while narrowing other lanes; installation of both traffic signals and lighting at an intersection, etc.

While the meaningful combined effects of risk factors or measures would be countless, and it would be unfeasible to take into account a considerable part of them within the project, the following actions were taken to account for this aspect as much as possible:

- To some extent, studies focusing on the **effect of each risk factor or measure in isolation** were sought, as these would allow a clear identification of the effect
- However, in some cases studies were found to deal with more than one risk factor or measure. This was the case, for example, of Accident Performance Functions developed on the basis of various geometric and traffic elements of an infrastructure (e.g. number of lanes, traffic, curve radius etc.). From the measures point of view, an example is rumble strips, for which studies were found with them implemented either at the edgeline of the road, or at the centerine, or at both. In these cases, **all related effects were coded**, and the study was indicated to concern all the topics for which effects were quantified.
- In the synopses of each topic, the fact of an effect being studies alone or in conjunction with others was taken into account. The conditions of implementation were clearly described in each case, and in the final synthesis, any **variation of the effect with respect to the implementation conditions** was explicitly mentioned. Similarly, the failure to consider the possible modifying conditions was also assessed in the study limitations.
- Eventually, each synopsis attempts to provide the best estimate of the "unique contribution" of a risk factor or measure, and to highlight the main modifying conditions or combined effects. However, this was achieved to a different degree in the different synopses.

5.4 HOT TOPICS

One of the main challenges of the SafetyCube work on infrastructure risks and measures was to **address the need of infrastructure stakeholders to conclude on the indicated "hot topics"**.

Throughout all stages of the analysis, particular emphasis was placed on these "hot topics", to make sure that sufficient high quality studies could be found, and with a broad geographical coverage, to allow for robust conclusions on these topics. Moreover, particular effort was made to conduct original meta-analyses on "hot topics", and eventually all 6 original meta-analyses carried out concerned "hot topics" (e.g. workzones, road safety audits & inspections, shoulder treatments etc.)

The results of this research clearly demonstrate that the "hot topics" suggested and ranked by road infrastructure stakeholders reflect much more than "trendy" road safety issues, and were proved indeed to be topics with high risk, or with measures with high potential of reducing risk.

Only in a few cases a risk or measure was flagged as a "hot topic" but analysis results did not confirm the importance of this topic. However, in some of these inconclusive cases, grey literature included more concrete results - which are referred to in the respective synopses.

There were also a few cases where a "hot topic" was not analysed, due to lack of studies (at least studies fulfilling the SafetyCube selection criteria).

Table Table 42 below presents the results regarding the SafetyCube infrastructure hot topics in terms of their eventual assessment and ranking.

Table 42: Ranking of infrastructure "hot topics" in terms of their effects on road safety

	Hot topic	
	Risks	**Measures**
High effect*	Workzone Length Low Curve Radius Alignment deficiencies - Absence of transition curves Alignment deficiencies - High Grade Presence of Tunnels Shoulder and roadside deficiencies -Absence of paved shoulders Shoulder and roadside deficiencies -Narrow shoulders Shoulder and roadside deficiencies - Risks associated with safety barriers and obstacles Shoulder and roadside deficiencies- sight obstructions (Landscape, Obstacles and Vegetation) At-grade junctions deficiencies-Number of conflict points Risk of different junction types At-grade junction deficiencies - skewness / junction angle At-grade junction deficiencies - Poor Sight Distance	Dynamic speed limits Dynamic speed display signs Installation of lighting & Improvement of existing lighting Workzones: Signage installation and improvement Shoulder implementation (shoulder type) Increase shoulder width Safety barriers installation; Change type of safety barriers Create clear-zone / remove obstacles & Increase width of clear-zone Traffic sign installation; Traffic sign maintenance Variable message signs Sight distance treatments
Low effect	Workzone duration Alignment deficiencies - Frequent curves Alignment deficiencies - Densely spaced junctions	Improve skewness or junction angle

* Red or Yellow risk colour code, Green or Light Green measure colour code
** Grey colour code

5.5 METHODOLOGY AND DATA LIMITATIONS

The limitations of this work should be noted. The process of **allocating colour codes** was related to **both the magnitude** of the safety impact observed for a risk or a measure – and the corresponding **presence of evidence**. It is possible for a measure with a light green colour code to have a greater impact on road safety than a measure coded green in actuality, if there was limited evidence of its impact recorded in the literature.

Findings are limited both by **the implemented literature search criteria and the quality of the studies identified**. The specific search strategy for each topic is explained in the supporting document of each synopsis in the appendix. However, since this research focuses on infrastructure, a common approach using the TRID search database was adopted since this is a rich source of information for research into the relationship between infrastructure design, layout and crashes/safety. However, TRID is an American database which may have artificially increased the number of American studies reviewed, as shown in Chapters 3 & 4. Nevertheless, the studies identified were of sufficiently high quality to inform understanding of the topic.

Due to resources constraints, a certain amount of prioritising during study coding was necessary for risks or measures with many identified studies. The **criteria for prioritising** within each synopsis is detailed in the supporting document. Across all topics, priority was given to existing relevant meta-analyses, as well as studies which considered crashes over changes in driving behaviour or effects of safety performance indicators such as speeds. This approach focused on studies with the highest methodological quality, however, it is possible that some detail may have been overlooked by not considering a broad range of methodological approaches. Finally, within the considered literature, crash risk and crash frequency are much more commonly studied than crash severity. For some topics this makes it difficult (or impossible) to consider the implications for injury mitigation.

5.5.1 Efficiency Evaluation Limitations

Similarly to road safety evaluation, the CBA aspect of this work has limitations. By far the most important limitation of using cost benefit analysis is its dependence on underlying assumptions that are not always straightforward to assess. Experience from the work carried out during WP5 shows that mainly the assumptions on three elements can play a decisive role:

- Assumptions about the effectiveness of the measures
- Assumptions about the costs of the measures
- Assumptions about the size of the target group

Most importantly, the scarse and fragmentary information available in the literature resulted in several cases for **a combination of information sources to be used for a single CBA**. In particular, a safety effect from a meta-analysis, being the most reliable effectiveness estimate, needed to be combined with measure cost information from another source, and applied for a customised case (unit of implementation and target group or number of crashes / casualties affected). Although every effort was made by SafetyCube experts to use as consistent sources as possible, and limit the number of different sources to be combined in a CBA, in several cases this was simply inevitable, in order to produce a CBA estimate. Even in these cases, particular caution was put on the transparent and substantiated combination of information.

Numerous examples can be given of CBA that – according to the assumptions made – easily change from highly beneficial to vastly inefficient or vice versa. It was exactly these uncertainties that led to the execution of a series of sensitivity analyses. These sensitivity analyses clearly showed what can be the (sometimes huge) consequences of changing some basic assumptions on measure costs or effectiveness.

The reader should realise that **the dependency on all these assumptions is not as such a weakness of the method but rather a weakness of the data that are usually available**. In this regard one can observe that in a number of the executed CBA the most uncertain elements appeared to be the ones that could have been expected to be the easiest to collect: the measure costs and the target numbers of crashes. One could expect that much knowledge on these elements should be available as they represent phenomena that are relatively straightforward to observe in the real world and therefore to collect data about; however, this was not eventually the case, as the documented information was often poor, fragmentary and unreliable.

6 Building the Inventory of Infrastructure risks and measures

Entering the information in the DSS database

This chapter describes the procedures adopted to ensure a high quality of the information included in the inventory of risks and measures. This information is then consistency checked before being recorded in the DSS database of effects and measures efficiency. The Chapter also provides illustrative examples of the infrastructure risks and measures results, as they appear on the DSS user interface.

6.1 QUALITY ASSURANCE (QA) PROCESS

The literature search, study coding and synopses creation for a particular risk factor or a measure was completed generally within the same SafetyCube partner organisation. In order to guarantee a comprehensive selection of studies per topic, low probability of coding errors, consistency within and between synopses a set of comprehensive QA criteria and procedures are set for each type of DSS contents.

6.1.1 Quality of coded templates

A common template and related set of coding instructions was developed to capture relevant information from each study in a manner that this information could be uniformly reported and shared across topics and WPs within the overall SafetyCube project.

Coding and interpreting the study results correctly require a good understanding of how exactly the studies were conducted. Even though the instructions for coding were detailed, these still allowed room for interpretation e.g. which design describes the study the best (if not mentioned by author), which estimates to include or exclude, what are essentially the weak points of the study etc. Therefore, **coding dedicated workshops and webinars** were held during the project to train coders and to define common approaches to emerging issues not specifically addressed by the guidelines.

Moreover, **a quality control procedure was established** in which all risk factors and safety measures were allocated to a primary and a secondary coding partner. The primary coding partner undertook the literature search, selected the papers for coding and coded these studies. The initial coded studies for each partner where shared between primary and secondary coding partners to confirm coding decisions. Once there was agreement on the coding of the initial studies, the rest of the studies were coded without sharing between the primary and secondary coding partners unless the studies were complicated or caused problems for the coders. These complicated studies which proved were discussed between the primary and secondary coding partner so as to reach consensus. Coders had the opportunity to have more than one study checked if they were uncertain.

A further quality check of coding is undertaken by a group of coding experts based on the analysis of result tables provided by the DSS. The analysis is aimed at finding empty fields, inappropiate values and inconsistencies. In case of mistakes that cannot easily be solved, specific requests can be submitted to the related coders to discuss problems.

6.1.2 Quality of synopses

In order to ensure a systematic and transparent procedure for including studies in the DSS, the guidelines provide concrete instructions for identifying potentially relevant studies and prioritising them for coding. The process was documented in a standard format to make the gradual reduction of relevant studies transparent. This documentation of each search is included in the corresponding supporting documents of the synopses.

Analysing and integrating the findings from different studies can be done in different ways, ranging from a merely descriptive approach to advanced statistical analyses. The guidelines describe several options and specify the related criteria and conditions.

A **Quality Assurance Committee**, consisting of eight Senior Experts from the SafetyCube partner institutes, guided and coordinated a subsequent Independent Expert review of all synopses. The main aim of this stage is to detect obvious errors or omissions in the messages and conclusions of the synopses. Synopses were assigned to a limited number of Senior Researchers with proven expertise in the relevant area. These reviewers focused on:

- The selection and prioritising of studies for coding, including the search terms that were used, the database(s) that were checked, and the transparency of the study selection.
- The contents of the 2-page synopsis summary, for example whether the abstract covered the most relevant findings, whether the reported results were valid and logical, and whether the summary sufficiently reflected the current state of knowledge.

If needed, as so decided by the QA Committee, a more thorough review was carried out and/or the original author(s) was/were asked to improve the synopsis.

Finally, for all synopses, the abstract and the overall conclusion - as expressed in the assigned colour code - were checked by one and the same expert in order to ensure readability as well as consistency of information within and between synopses.

6.1.3 Quality of efficiency analysis

Efficiency analysis were supported by using a common tool: the *Economic Efficiency Evaluation* (*E^3*) *calculator*. The SafetyCube E^3 tool was used to perform cost-benefit analysis based on a set of input data collected and required by the tool: the effectiveness of the measure, unit of implementation and time horizon, the target group, and the measure costs. About crash costs, the improved SafetyCube estimates for EU countries were used in all CBAs. Furthermore, sensitivity analysis of the CBA results were performed to address uncertainty in the safety effects and costs as found in the literature.

All results and assumptions were summarized in a two-page synopsis document. All these synopses were checked by one Senior Expert to check assumptions made and accuracy of the results, as well as to ensure readability as well as consistency of information within and between synopses.

6.2 DEVELOPING THE DSS DATABASE

All the information constituting the Inventory of Infrastructure risks and measures is recorded in a standard way in the DSS database and is available to the DSS users.

The main type of DSS contents are:

- SafetyCube coded studies
- SafetyCube synopses on the effects of risk factors or measures and synopses on the economic efficiency of measures

Before a DSS content is published and becomes available to the DSS user a number of steps should be accomplished.

6.2.1 SafetyCube coded studies

Results from a relevant study are coded according to a dedicated template as described in the guidelines (Martensen, H. et al.,2017). The template, described in section 2.2.2, consists of an Excel-file with seven sheets:

- **Core info**, containing core variables that should be considered for every study.
- **Results**, providing the numerical and statistical details of effects that are reported in a given study.
- **Flexible info**, containing flexible variables that should only be used when they are relevant for coding the specific study at hand
- **Custom info**, aiming at addressing variables or values/levels not included in the template that are needed for a correct representation of the study
- **$exposure**, including the details of exposure variable(s)
- **$outcome**, including the details of the outcome(s)
- **Summary**, intended to provide a synthesis of the design and the conclusions

An example of a **Results sheet** in the excel template, completed for a study on the effect of road lighting installation is provided in the **Figure 8** below:

☐ Differences between effects	Effect 1	Effect 2	Effect 3	Effect 4	Effect 5	Effect 6
Road user profile - Modes	All	All	Pedestrian	Pedestrian		
Road network profile - Area	All	All	All	All	All	Urban road
Road network profile - Segments					Pedestrian crossing	Two-way roads
Accident severities	Fatal	Injury	Fatal	Injury	Injury	Injury
Road lighting - Test group	Darkness illuminated road	Darkness illuminated road	Darkness illuminated road	Darkness illuminated road	Darkness illuminated road	Darkness illuminated road
Road lighting - Reference group	Darkness no illumination	Darkness no illumination	Darkness no illumination	Darkness no illumination	Darkness no illumination	Darkness no illumination
Measure of effect/association	Percent change	Percent change	Percent change	Percent change	Percent change	Percent change
Specifications	Percent change in accident num	Percent change in accident num	Percent change in accident num	Percent change in accident num	Percent change in accident num	Percent change in accident num
Estimate	-52.0000	-26.0000	-78.0000	-51.0000	-53.0000	-10.0000
Standard error of estimate						
Statistic [name(parameters)=x]						
p-value						
Sample size (x or n1=x1; n2=x2)						
Confidence level	95.0000	95.0000	95.0000	95.0000	95.0000	95.0000
Lower limit	-59.0000	-33.0000	-88.0000	-63.0000	-37.0000	-41.0000
Upper limit	-45.0000	-19.0000	-62.0000	-36.0000	-66.0000	36.0000
Adjustment variables/Covariates						
Conclusion	Significant positive effect on ro	Significant positive effect on ro	Significant positive effect on ro	Significant positive effect on ro	Significant positive effect on ro	Non-significant effect on road
Comments	Based on 16 estimates from 11	Summary estimate based on st	Based on 3 estimates from 2 st	Based on 9 estimates from 7 st	Based on 4 estimates from 3 st	Effect denotes accidents on ro

Figure 8: Example of coded template (results sheet) effect of road lighting

When a coding template is completed for a study, it is located in a shared repository. Periodically, the coding templates are processed by an automatic routine checking for missing (important) data and inconsistencies. If no errors are detected, the information in the template is recorded on the DSS database. Otherwise, coders might be contacted for clarifications/corrections.

6.2.2 SafetyCube synopses

Each synopsis is coupled for searching purpose with a record in the DSS database storing the synopsis title, synopsis abstract, references to the studies coded in the preparation of the synopsis, the coder name and the main searching information: Work Package, taxonomy and keywords.

This information is recorded by the synopsis author(s) in an excel coding sheet for synopses. When a synopsis is completed, a .zip file containing the pdf of the synopsis and the synopsis excel coding sheet is located in a shared repository.

6.3 DSS OUTPUT

The SafetyCube DSS (Decision Support System) is available at: http://www.roadsafety-dss.eu (see **Figure 9**). Its pilot operation started early 2017; since then the system has been updated continuously and this will process will continue until April 2018 (end of the SafetyCube project) and beyond. The system consists of the backend database which was described in the previous sub-chapter 6.2, and the related user interface, and the way they integrate (namely through the DSS Search Engine and the related database queries).

Figure 9. SafetyCube DSS home page

The DSS has five different entry points (keywords, risk factors, measures, road user groups and accident categories), allowing searches leading through different "paths" to the results of the two pillars of SafetyCube, i.e. risk factors and measures. The DSS results pages present quantitative and qualitative information about a wide range of crash risks, and the effectiveness and cost-benefit (where possible) of road safety measures. The detailed description of the DSS is beyond the scope of this report. As an example of the contents displayed in the DSS after a specific query, an example of each, a page of topic search results and one of single study information, is presented below.

6.3.1 Search page for infrastructure topics

When "Risk Factors" is selected as entry point, the SafetyCube taxonomy of crash risks will open, sorted by the domains "Road User", "Infrastructure" and "Vehicle" (see **Figure 10**). Likewise, if the entry point "Road Safety Measures" were selected, the SafetyCube taxonomy of measures would appear, including, in addition to the three domains, a fourth domain on "Post Impact Care".

Figure 10: Risk Factors Search: the SafetyCube taxonomy of crash risks on the DSS.

Selecting one of the taxonomy's entries will take the user further to the respective results page (see next section hereunder).

6.3.2 Results pages for infrastructure topics

Upon selecting an entry on one of the above lists (risk factors or measures), the main results page will appear. The results consist of (see Figures 11, 12):

- Short **introductory texts and the colour code(s)**, describing the risks or the effectiveness of measures
- Links to one or more available **SafetyCube synopses** on the issue (pdf link button(s) next to the colour code, see Figure3).
- A **table listing the available meta-analyses and other coded studies** in the SafetyCube database together with their main characteristics such as design, country, and year of publication. Selecting a study from the Table will lead the user to the individual study page (see next section).
- Depending on the selected domain, **adaptive search filters** are available on the left side of the results page. Filters include: keyword, specific risk factor (corresponding to the most

detailed taxonomy level), road user group, road type, country. The keyword filter appears only when entering from the "keyword" or "road user group" entry point, and allows the user to "un-filter" the results and obtain all the studies related to the risk factor or measure (and not only those related to the keyword or road user group).

- A button which **links to related measures** (if the results page is in the risks domain) **or to related risk factors** (if the results page is in the measures domain).

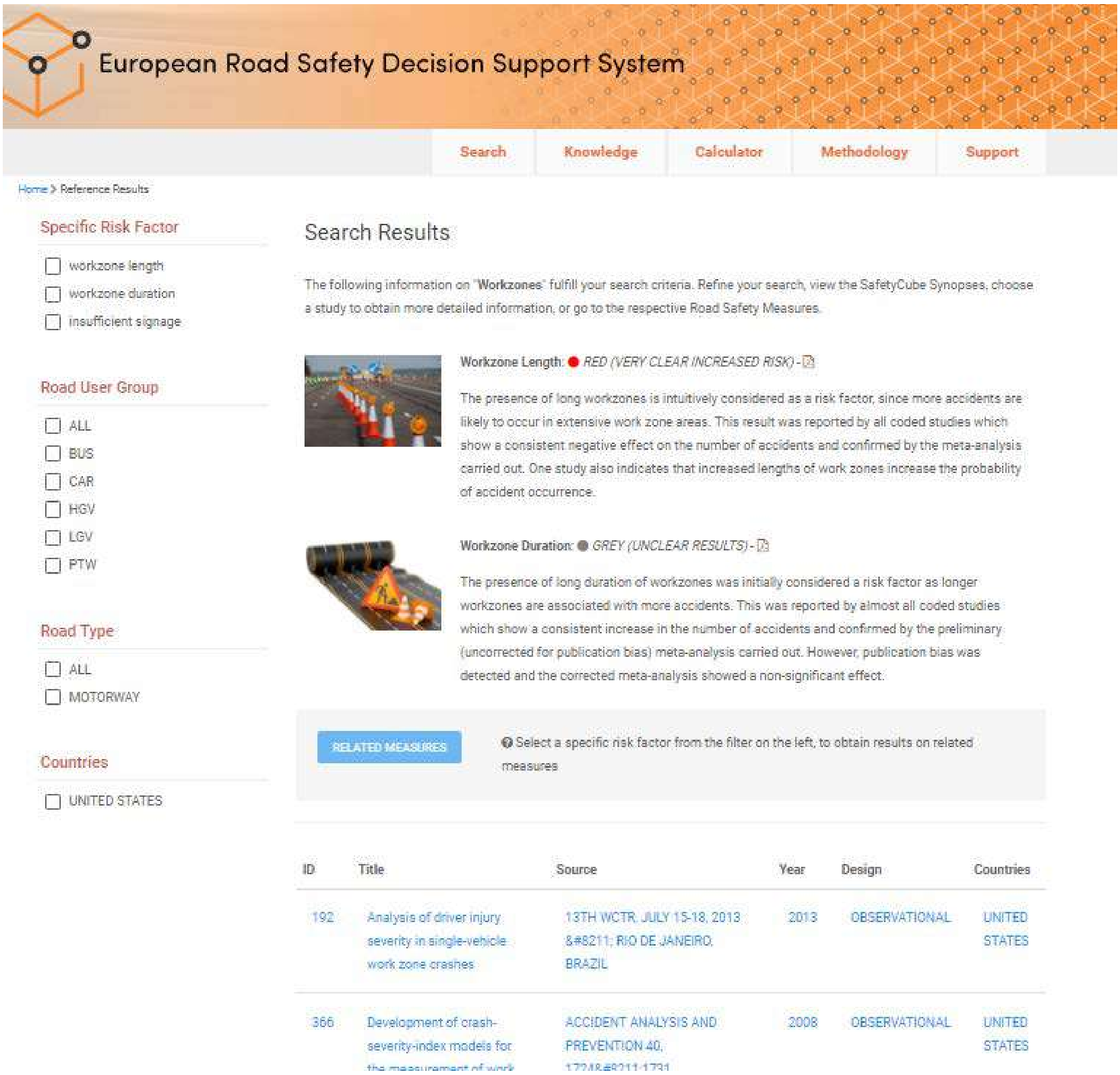


Fig.11. The Results Page of risk factor "work zones"

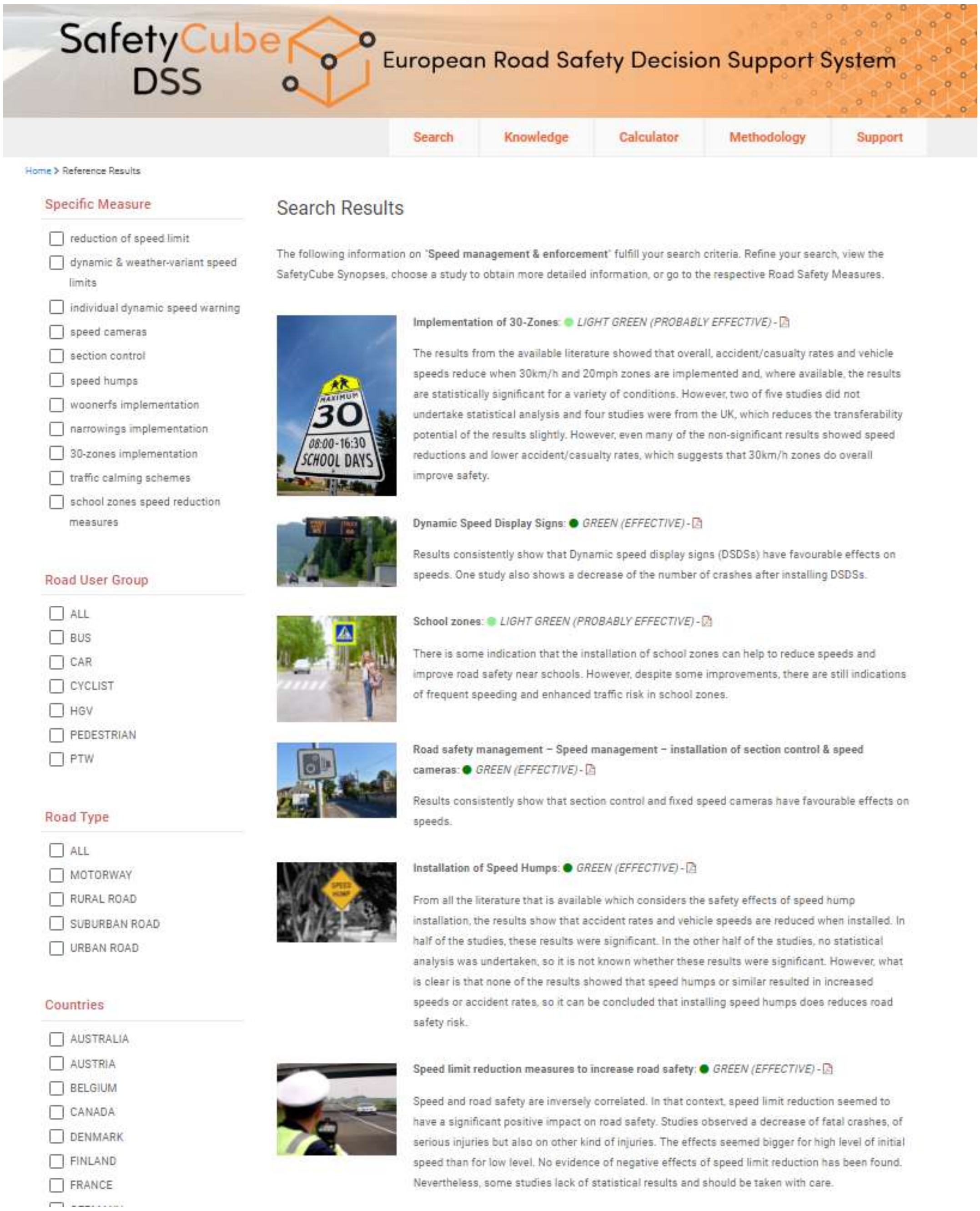
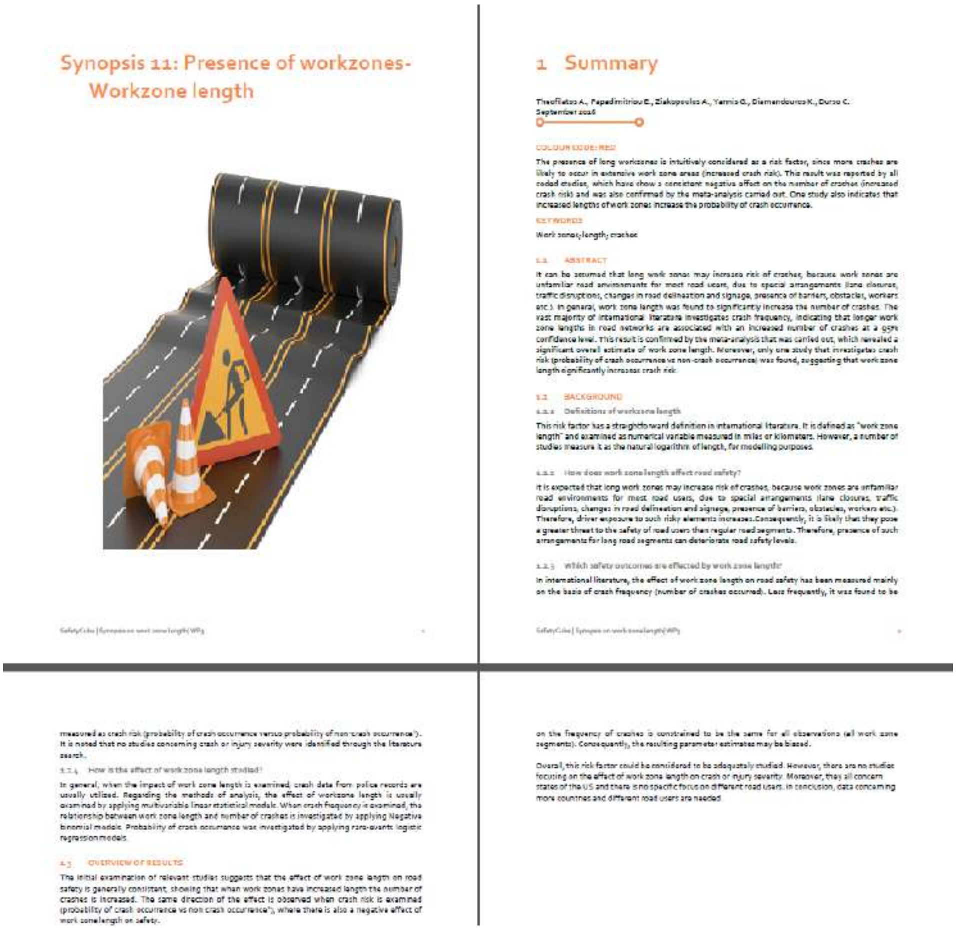


Fig. 12: The results page for the infrastructure measure "Speed management and enforcement"

All the Synopses produced are also listed and available for download via the **Knowledge** tab of the SafetyCube DSS.



Synopsis 11: Presence of workzones- Workzone length

1 Summary

Theofilatos A., Papadimitriou E., Ziakopoulos A., Yannis G., Diamandouros K., Durso C.
September 2016

COLOUR CODE: RED

The presence of long workzones is intuitively considered as a risk factor, since more crashes are likely to occur in extensive work zone areas (increased crash risk). This result was reported by all coded studies, which have show a consistent negative effect on the number of crashes (increased crash risk) and was also confirmed by the meta-analysis carried out. One study also indicates that increased lengths of work zones increase the probability of crash occurrence.

KEYWORDS

Work zones; length; crashes

1.1 ABSTRACT

It can be assumed that long work zones may increase risk of crashes, because work zones are unfamiliar road environments for most road users, due to special arrangements (lane closures, traffic disruptions, changes in road delineation and signage, presence of barriers, obstacles, workers etc.). In general, work zone length was found to significantly increase the number of crashes. The vast majority of international literature investigates crash frequency, indicating that longer work zone lengths in road networks are associated with an increased number of crashes at a 95% confidence level. This result is confirmed by the meta-analysis that was carried out, which revealed a significant overall estimate of work zone length. Moreover, only one study that investigates crash risk (probability of crash occurrence vs non-crash occurrence) was found, suggesting that work zone length significantly increases crash risk.

1.2 BACKGROUND

1.2.1 Definitions of workzone length

This risk factor has a straightforward definition in international literature. It is defined as "work zone length" and examined as numerical variable measured in miles or kilometers. However, a number of studies measure it as the natural logarithm of length, for modelling purposes.

1.2.2 How does work zone length affect road safety?

It is expected that long work zones may increase risk of crashes, because work zones are unfamiliar road environments for most road users, due to special arrangements (lane closures, traffic disruptions, changes in road delineation and signage, presence of barriers, obstacles, workers etc.). Therefore, driver exposure to such risky elements increases. Consequently, it is likely that they pose a greater threat to the safety of road users than regular road segments. Therefore, presence of such arrangements for long road segments can deteriorate road safety levels.

1.2.3 Which safety outcomes are affected by work zone length?

In international literature, the effect of work zone length on road safety has been measured mainly on the basis of crash frequency (number of crashes occurred). Less frequently, it was found to be measured as crash risk (probability of crash occurrence versus probability of non-crash occurrence"). It is noted that no studies concerning crash or injury severity were identified through the literature search.

1.2.4 How is the effect of work zone length studied?

In general, when the impact of work zone length is examined, crash data from police records are usually utilized. Regarding the methods of analysis, the effect of workzone length is usually examined by applying multivariable linear statistical models. When crash frequency is examined, the relationship between work zone length and number of crashes is investigated by applying Negative binomial models. Probability of crash occurrence was investigated by applying rare-events logistic regression models.

1.3 OVERVIEW OF RESULTS

The initial examination of relevant studies suggests that the effect of work zone length on road safety is generally consistent, showing that when work zones have increased length the number of crashes is increased. The same direction of the effect is observed when crash risk is examined (probability of crash occurrence vs non crash occurrence"), where there is also a negative effect of work zone length on safety.

on the frequency of crashes is constrained to be the same for all observations (all work zone segments). Consequently, the resulting parameter estimates may be biased.

Overall, this risk factor could be considered to be adequately studied. However, there are no studies focusing on the effect of work zone length on crash or injury severity. Moreover, they all concern states of the US and there is no specific focus on different road users. In conclusion, data concerning more countries and different road users are needed.

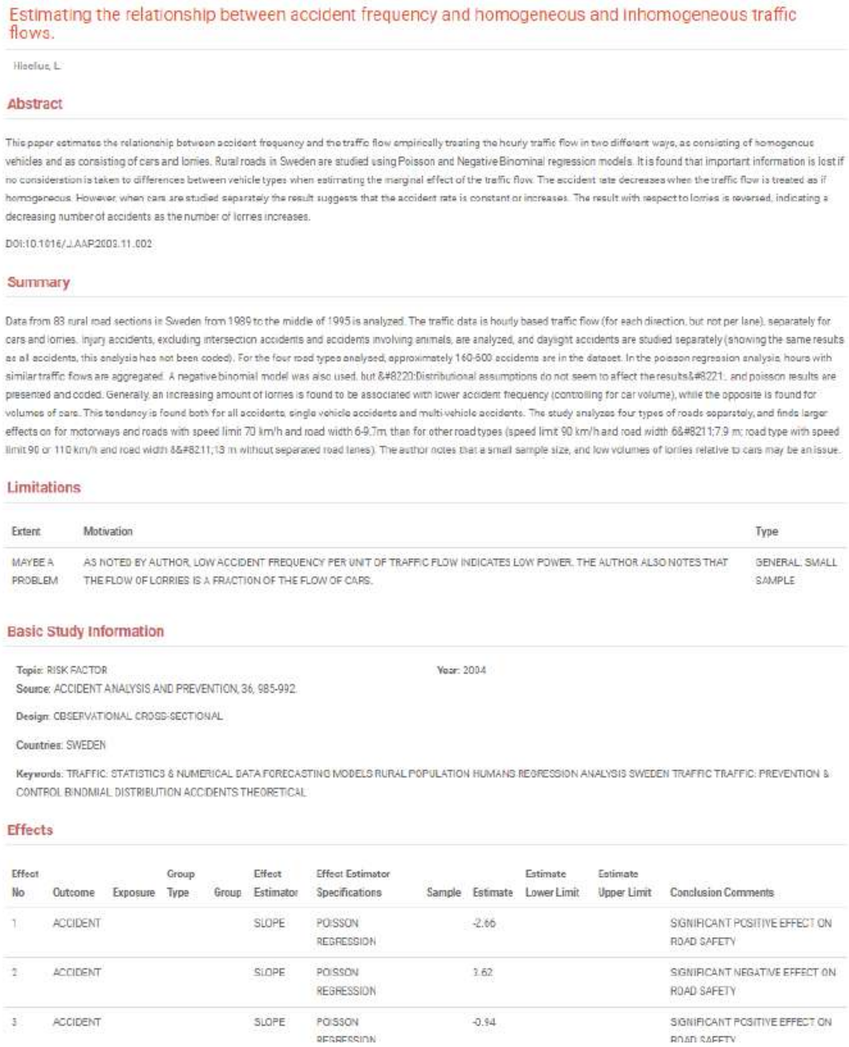
Figure 13. Snapshot of SafetyCube Synopsis for risk factor "work zone length"

6.3.3 Individual study pages for infrastructure studies

The individual study results (see Figure 14) includes the study abstract (as it appears in the original publication), the related URL, and a table of all risk / measure safety effects available in the study containing:

- test and reference condition (e.g. exposed vs. not exposed)
- type of outcome (e.g. injury severity)
- type of estimate (e.g. CMF, odds ratio)
- statistical significance.

The page also includes a summary of the main study features and findings written by the SafetyCube expert who analysed and coded the study, as well as an explicit outline of potential methodological issues or biases, also as identified by the SafetyCube expert.



Estimating the relationship between accident frequency and homogeneous and inhomogeneous traffic flows.

Hiselius, L.

Abstract

This paper estimates the relationship between accident frequency and the traffic flow empirically treating the hourly traffic flow in two different ways, as consisting of homogenous vehicles and as consisting of cars and lorries. Rural roads in Sweden are studied using Poisson and Negative Binominal regression models. It is found that important information is lost if no consideration is taken to differences between vehicle types when estimating the marginal effect of the traffic flow. The accident rate decreases when the traffic flow is treated as if homogeneous. However, when cars are studied separately the result suggests that the accident rate is constant or increases. The result with respect to lorries is reversed, indicating a decreasing number of accidents as the number of lorries increases.

DOI:10.1016/J.AAP.2003.11.002

Summary

Data from 83 rural road sections in Sweden from 1989 to the middle of 1995 is analyzed. The traffic data is hourly based traffic flow (for each direction, but not per lane), separately for cars and lorries. Injury accidents, excluding intersection accidents and accidents involving animals, are analyzed, and daylight accidents are studied separately (showing the same results as all accidents, this analysis has not been coded). For the four road types analysed, approximately 160-600 accidents are in the dataset. In the poisson regression analysis, hours with similar traffic flows are aggregated. A negative binomial model was also used, but “Distributional assumptions do not seem to affect the results”, and poisson results are presented and coded. Generally, an increasing amount of lorries is found to be associated with lower accident frequency (controlling for car volume), while the opposite is found for volumes of cars. This tendency is found both for all accidents, single vehicle accidents and multi-vehicle accidents. The study analyzes four types of roads separately, and finds larger effects on for motorways and roads with speed limit 70 km/h and road width 6-9.7m than for other road types (speed limit 90 km/h and road width 6–7.9 m; road type with speed limit 90 or 110 km/h and road width 8–13 m without separated road lanes). The author notes that a small sample size, and low volumes of lorries relative to cars may be an issue.

Limitations

Extent	Motivation	Type
MAYBE A PROBLEM	AS NOTED BY AUTHOR, LOW ACCIDENT FREQUENCY PER UNIT OF TRAFFIC FLOW INDICATES LOW POWER. THE AUTHOR ALSO NOTES THAT THE FLOW OF LORRIES IS A FRACTION OF THE FLOW OF CARS.	GENERAL: SMALL SAMPLE

Basic Study Information

Topic: RISK FACTOR **Year:** 2004
Source: ACCIDENT ANALYSIS AND PREVENTION, 36, 985-992.

Design: OBSERVATIONAL CROSS-SECTIONAL

Countries: SWEDEN

Keywords: TRAFFIC: STATISTICS & NUMERICAL DATA FORECASTING MODELS RURAL POPULATION HUMANS REGRESSION ANALYSIS SWEDEN TRAFFIC TRAFFIC: PREVENTION & CONTROL BINOMIAL DISTRIBUTION ACCIDENTS THEORETICAL

Effects

Effect No	Outcome	Exposure	Group Type	Group	Effect Estimator	Effect Estimator Specifications	Sample	Estimate	Estimate Lower Limit	Estimate Upper Limit	Conclusion Comments
1	ACCIDENT				SLOPE	POISSON REGRESSION		-2.66			SIGNIFICANT POSITIVE EFFECT ON ROAD SAFETY
2	ACCIDENT				SLOPE	POISSON REGRESSION		3.62			SIGNIFICANT NEGATIVE EFFECT ON ROAD SAFETY
3	ACCIDENT				SLOPE	POISSON REGRESSION		-0.94			SIGNIFICANT POSITIVE EFFECT ON ROAD SAFETY

Figure 14 The Individual Study page for a study concerning "traffic flow" as a risk factor

6.3.4 Linking risks and measures within a systems approach

In SafetyCube, all risks are intended to be linked to measures that have the potential of reducing this risk, and vice versa. The links between risks and measures are based on **a dedicated SafetyCube model under development** categorising risks as to:

- generic ones, i.e. concerning the general state of the system (e.g. design of roads or vehicles, knowledge of the road users, etc.) or
- "circumstantial" ones, i.e. concerning the transient state of the system at the moment the crash occurred (e.g. defects, environmental conditions, road-user impairment, etc.).

Similarly, measures are categorised as:

- addressing generic risks, i.e. improving the general state of the system
- addressing "circumstantial" risks, i.e. preventing or mitigating circumstantial risks such as speeding, road user impairment, visibility etc.

Moreover, risks and measures are associated with:

- specific accident categories, namely those used in the respective DSS entry point.
- specific accident phases: pre-crash (typically, but not exclusively, including generic factors), crash (typically, but not exclusively, including circumstantial factors) or crash consequences (severity)

All these elements are integrated and taken into account when checking for measures that should be considered as remedies for a risk factor in question. Moreover, by linking risk factors to measures from different domains, a **systems approach** is emphasized for the user. A full description of the links developed between risks and measures is beyond the scope of this report, however an example is indicatively presented below:

When looking for measures linked to a road user related risk like "speeding", the user will be guided to measures that address road user (campaigns, demerit point systems) or infrastructure (speed humps, section control) or the vehicle (ISA, adaptive cruise control) - see Figure 15.

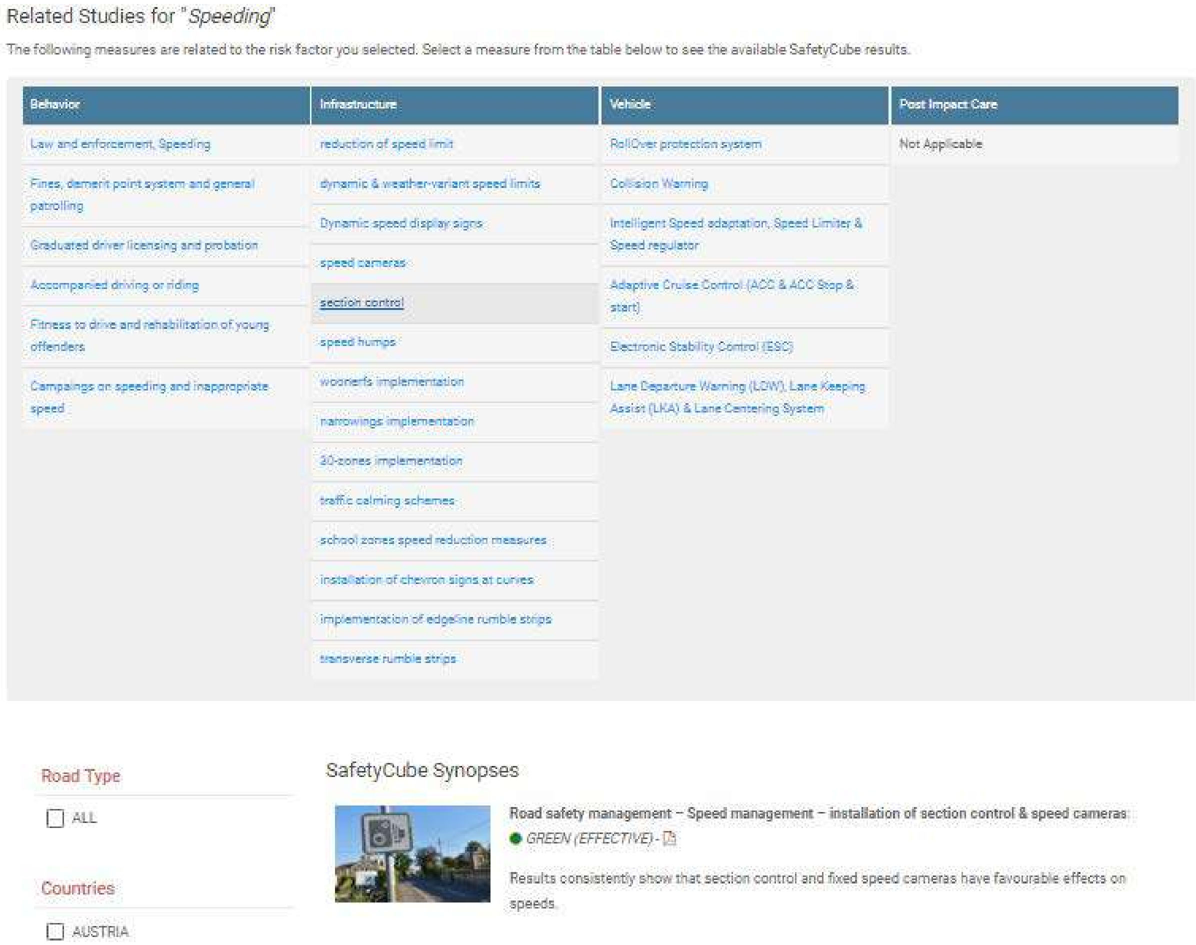


Figure 15. Related measures for the risk factor "speeding" - selection of the measure "section control"

6.3.1 The Calculator

The calculator for Economic Efficiency Evaluation (E3) of road safety measures will also be available through the DSS (currently under development). It will allow the user to retrieve existing SafetyCube CBAs and possibly adapt them with their own data / for their own country etc. It will also allow users to conduct their own CBA for any measure they wish.

7 Conclusions

Within the project SafetyCube an inventory of road infrastructure related risk factors and measures was developed. Risk factors and measures have been systematically analysed and assessed with regard to their effect on road safety. This inventory brings together European and international evidence on both road safety risks and the related interventions that effectively mitigate these threats. Further, the available knowledge is easily accessible for decision makers and other stakeholders of all kinds by the web based Road Safety Decision Support System (https://www.roadsafety-dss.eu/).

Overhall, the inventory includes more than **240** coded studies on infrastructure related risk factors and more than **260** studies on infrastructure related mesures. Moreover, **39 synopses** were written for road infrastructure-related risk factors, **48 synopses** on road infrastructure measures and **19 CBA synopses**.

One prominent feature of the DSS is that interlinked information is available on both risk factors and measures across the fields behaviour, infrastructure, vehicles and post-impact care within a systems approach. This should help decision makers to easily find effective and efficient measures for an existing problem or gaining information which problems can be tackled by a specific measure. The linkage of risks and measures across the fields human, infrastructure and vehicle should make users aware that solutions can be found in various areas.

Measuring the effectiveness of measures and quantifying risk factors effects is challenging for various reasons. However, these challenges highlight the importance of evidence based decision making and the need for evaluation studies especially for infrastructure "hot topics".

In order to keep the included evidences up to date a constant updating process is needed. The Road Safety DSS is expected to remain open for updates and for additional synopses after the SafetyCube project. In order to maintain an adequate level of scientific quality, a similar quality assurance procedure will be followed.

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Appendix A Risk factor Abstracts

EXPOSURE

Effect of traffic volume on road safety – Abstract

Colour code: Red

Traffic volume, or traffic flow, denotes the number of vehicles passing a given point or section of a road for a given time unit. The relationship between crashes and traffic volume appears to be non-linear. Most reviewed studies find that higher traffic volumes are associated with a net increase of crashes. However, the number of crashes increases less than proportional to traffic volume. This indicates that an increase in traffic volume is associated with a lower risk for each road user (since risk = crashes/exposure). Several studies find that the effect of traffic volume on crash occurrence differs between crash types. For multi-vehicle crashes, most studies indicate that both the frequency and the risk of such crashes increase at higher traffic volumes. While it seems clear that traffic volume is related to crash occurrence, the form of this relationship (which might differ for different crash types), and the mechanism explaining these relationships remain somewhat unclear. It is also not clear how traffic volume affects road safety on different road types. The current results are mostly based on motorways, as this is what is currently available in the literature.

Congestion as a risk factor – Abstract

Colour code: Yellow

Congestion refers to a traffic state with slow-moving or still-standing traffic, which could occur due to road, traffic, or weather conditions. Congestion might affect road safety due to decreased speed (less severe crashes), high degrees of speed variation within and between lanes increasing the complexity of driving (more crashes), or by creating stress (detrimental for driver behaviour). Most studies define congestion based on travel time, speed, or traffic density. Studies using a density-based definition of congestion (volume/capacity-ratio) report congestion to be associated with fewer crashes in total, but find different tendencies for single-vehicle and multi-vehicle crashes. Studies defining congestion by increased travel time or decreased speed generally find congestion to be associated with a higher number of crashes (including injury crashes), but this is not reported under all conditions. Due to a low number of relatively dissimilar studies, the effect and potential transferability are uncertain. Most reviewed studies are from the United States, and all are based on motorways, which could explain the somewhat surprising result that injury accidents are not found to decrease in congested traffic states. No distinctions are made between different road users.

Occurrence of secondary crashes

Colour code: Yellow

The occurrence of an initial crash or incident (e.g., vehicle breakdown) may increase the risk of secondary crashes and incidents occurring, by causing (non-recurrent) congestion, traffic flow disruption and/or driver distraction. Studies find that 0.4 to 8.4% of crashes on motorways are secondary, i.e. caused at least in part by a prior crash or incident. Most secondary crashes occur in the same direction and upstream of a prior crash, and a longer duration of the prior crash/incident is associated with greater risk of secondary crash occurrence. The methodology applied for classifying crashes as secondary varies greatly among studies, but is generally based on estimates of the queue caused by the prior crash/incident. The available literature has not investigated the extent of secondary crashes on roads other than motorways, nor the risk for different transportation modes, and all the reviewed studies are from the United States.

Safety-in-numbers and other risks associated with traffic composition

Colour code: Red for VRU

Colour code: Grey for HGV

Traffic composition refers to the share of different groups of road users in traffic (e.g. cars, pedestrians, cyclists, heavy goods vehicles, powered two wheelers). An increase in the volume of cyclists and pedestrians is associated with a net increase in crashes (between cyclists/ pedestrians and motor vehicles), but this increase is less than would be expected for the proportional increase in volume, corresponding to lower risk for each road user. A meta-analysis estimated that a doubling of the volumes of pedestrians or cyclists would correspond to a 41 % increase in crashes (across road types and areas). This is in accordance with a "Safety-in-numbers" effect (more cyclists/ pedestrian corresponds to a lower crash risk for each cyclist/pedestrian), but it remains unclear if the lower risk is *caused* by the higher numbers of pedestrians/cyclists. The effect of the share of heavy goods vehicles on road safety is unclear (few studies with mixed results), and no studies were found on the share of powered two wheelers or public transport.

Distribution of flow over arms at junctions

Colour code: Grey

In the case where primary and secondary roads cross, the distribution of traffic flow over the arms of a junction can introduce a non-trivial risk. In general, it is not easy to make a clear conclusion about the effect of the distribution of traffic flow over the arms of a junction. This is due to the different variables that the different studies used to express the specific risk factor. In situations where there is an increase to: (i) the traffic on the minor or major road, (ii) the ratio of major road traffic to the minor road traffic, or (iii) the number of turn lanes, crash frequency tends to increase. On the contrary, in some cases of flow imbalance between the junction branches, the number of crashes reduces. Crash severity also increases with an increase in the major road's Annual Average Daily Traffic (AADT). Finally, the vote-count analysis undertaken showed that difference in traffic flows between the arms of a junction has an overall negative effect on road crash frequency for 3-legged, 4-legged, signalised and non- signalised junctions (results from 7 studies), but a positive effect on crash severity (i.e. less severe crashes) for non-signalised, 3-legged and 4-legged junctions (results from 1 study).

Absence of access control

Colour code: Red

Absence of access control as a risk factor means that there have been no measures to reduce the number of (private) driveways along a public road. From the international literature it appears that a higher access point density on road segments has a negative effect on road safety. Only negative interdependencies were presented, two of which were statistically significant. Moreover, for corner clearance (i.e. the distance between an intersection and the nearest driveway) it seems that the length is positively correlated to road safety, i.e. a greater distance increases road safety. All four identified papers focused on crash frequency and were – apart from one meta-analysis – carried out in the United States. However, the results seem generally transferable.

ROAD TYPE

Road functional class

Colour code: Yellow

For most countries, roads are generally organised into classes which reflect the main function and traffic type they are designed for. This is often described as road functional class. In the literature analysed, all road classes were considered from minor local roads to major arterial roads and motorways, but the categorisation used varied across each country and study, which made road functional class a complicated topic to analyse. Studies used either crash frequency (and in one case, crash rate), casualty frequency or injury severity as a measure of the risk of road functional class. It was found that, overall, minor roads were statistically significantly safer than major roads in terms of both crash and casualty frequency and also injury severity. This result was reversed when examining particular cases (e.g. collisions only involving tractor-trailers). However, not all studies found statistically significant differences, and the overall results may be over-generalised due to having to group road class categories across studies to allow a cross-study analysis.

ROAD SURFACE

Inadequate friction

Colour code: Red

This synopsis is based on a methodological paper exploring the feasibility of developing a formal synthesis of functional relationships estimated for different data sets and differing with respect both to the variables included and the mathematical form of the estimated relationships. Studies estimating a functional relationship between road surface friction and crash rate were formally synthesised. Models allowing for non-linearity in the relationship between traffic volume and the number of crashes predict that the number of crashes (controlling for traffic volume) will be about 55 % lower when skid resistance (an estimator of friction varying between 0 (no friction) and 100 (maximum friction) increases from 10 to 90. The direction of the functional relationship (higher friction = fewer crashes) is highly consistent, but its exact shape and strength varies considerably between studies.

ROAD ENVIRONMENT

Darkness

Colour code:

- **Red for pedestrians**
- **Green for cars**
- **Yellow for two-wheelers**

When considering the total number of crashes, the absence of daylight is associated with an increased crash risk. This effect is confirmed for pedestrians for which the crash risk is systematically higher in darkness than in daylight. The crash risk for pedestrian is estimated to be 2 to 4 times higher in such conditions. Also for powered two-wheelers the crash risk in darkness seems to be higher than in daylight, but to a lesser extent (less than 2 times higher). For cars, results do not show any significant impact of darkness. Fatalities and serious injuries are more likely in darkness than in daylight, while for slight injury crashes it is the other way round. Hence, it can be concluded that crashes in darkness are more severe.

Poor visibility – Fog

Colour code: Yellow

The effects of fog on accident occurrence and severity have been found to be somewhat inconsistent. Out of the four reviewed studies, two studies found generally unfavourable effects on road safety in terms of the frequency and/or severity of accidents, while two studies generally did not find a significant effect of fog on accident frequency and/or severity. Literature provides some evidence of lower numbers of accidents involving two-wheelers during fog, but this is possibly the result of changes in traffic volumes. However, since exposure was not accounted for, this cannot be confirmed.

The risks associated with fog mostly relate to the reduced visibility, although there also is a possibility of reduced grip due to viscous aquaplaning. These risks might be offset by more careful road user behaviour. The actual accident occurrence is influenced by changes in mobility (traffic volume) as well – in particular for unprotected road users like pedestrians, cyclists, and motorcyclists. So far, these mobility effects have not been accounted for, leaving the true risk unknown.

Effects of rain on road safety

Colour code:
- Red for motor vehicles
-Grey for other road users

Rain has been consistently found to be a risk factor (in Europe) in the sense that the injury crash rate (the number of injury crashes per vehicle or km-driven) is higher during rain than in comparable situations without rain. This has however, mainly been studied for motor vehicles. It is not clear whether it is true for other road users as well. The effect on fatal or severe crashes is less reliable. Crashes in rainy conditions have been found to be less severe (except in Scandinavian countries).

The net effect on crash occurrence can differ substantially from the risk effect of rain, because adverse weather conditions also affect the mobility, in particular mobility of vulnerable road users who are more exposed to the weather. Consequently, the net effect on crash occurrence yields much more mixed results with decreases in crash numbers observed more often for vulnerable road users and in urban areas. More research is needed to disentangle risk effects and mobility effects for vulnerable road users.

Effects of frost and snow on road safety

Colour code: Grey

The effects of snow and frost on crash occurrence and risk have been found to be very inconsistent. For **frost**, *if* results are significant, they indicate a reduced crash occurrence (i.e. an improvement of road safety). Only on motorways frost tends to lead to an increased crash risk. For **snow** the results are more inconsistent with somewhat more positive effects (i.e. reduction of crashes) than negative effects (increased crash numbers). The first snow after a time of no snow seems to be consistently associated with a higher crash risk.

The risks associated with frost and snow are slippery roads, and for snow also reduced visibility. These risks might be offset by more careful road user behaviour. However, much more likely the actual crash risk is influenced by a reduction of mobility (traffic volume) – in particular for unprotected road users like pedestrians, cyclists, and motorcyclists. So far, these mobility effects have been insufficiently accounted for, leaving the true risk unknown.

WORKZONES

Presence of workzones-Workzone length

Colour code: Red

It can be assumed that long work zones are detrimental to road safety, because work zones are unfamiliar road environments for most road users, due to special arrangements (lane closures, traffic disruptions, changes in road delineation and signage, presence of barriers, obstacles, workers etc.). In general, work zone length was found to significantly increase the number of crashes. The vast majority of international literature investigates crash frequency, indicating that longer work zone lengths in road networks are associated with an increased number of crashes at a 95% confidence level. This result is confirmed by the meta-analysis that was carried out, which revealed a significant overall estimate of work zone length. Moreover, one study that investigated crash risk (probability of crash occurrence vs non-crash occurrence) was found, suggesting that work zone length significantly increases crash risk. On the basis of these results, it is expected that workzone length treatments will have analogous positive effects on road safety.

Presence of workzones - Workzone duration

Colour code: Yellow

Long duration work zones can cause safety issues to drivers, because work zones are unfamiliar road environments for most road users, due to special arrangements. The vast majority of international literature investigates crash frequency, indicating that increased duration of works in road networks leads to an increased number of crashes at a 95% confidence level. However, a meta-analysis that was carried out, revealed a non-significant overall estimate of work zone duration after correcting for publication bias. Moreover, only one study was found to investigate crash risk (probability of crash occurrence vs non-crash occurrence), suggesting that work zone duration has no significant effect on crash risk. On the basis of these results, it is expected that workzone duration decreases will have analogous effects on road safety, which can be positive but not statistically significant. Finally, it is noted that this synopsis deals with road users' safety and not road worker safety

ALIGNEMENT DEFICIENCIES - ROAD SEGMENTS

Low curve radius

Colour code: Red

Average crash rates are higher on horizontal curves than on straight sections of rural two-lane highways. Radius or degree of curvature consistently tops the list of geometry variables that most significantly affect operating speeds and crash experience on horizontal curves. The crash rate increases with lower curve radii (tighter curves), with strong increase for radii smaller than 200 metres. In general, sharp curves in combination with long straight sections, sharp vertical sag or sharp crest curves, and a sequence of gentler curves are factors that increase risk in curves. For specific groups of drivers, such as motor cyclists and truck drivers, curves with low radii may be more risky than for other drivers and may require additional risk mitigating measures. The analysis of coded studies confirmed that curves with low radii have a higher crash risk. Moreover this analysis showed that crash modification functions for curve radius are very different for curve radii < 200 metres, with particular steep functions for Germany and USA. Based on USA rural highway studies, the analysis of coded studies found steeper crash modification factors for fatal/injury crashes than for Property Damage Only (PDO) crashes. It was also found that low curve radius is especially risky in interaction with vertical sag or crest curves, and that curve radius was the strongest predictor for motorcycle-to-barrier crashes. On the basis of these results, it is expected that the measure of increasing horizontal curve radius will have analogous positive effects on road safety.

Absence of transition curves

Colour code: Yellow

Transition curves are defined as the transition between a tangent and a circular curve. In a transition curve, the curve radius is not constant but gradually changes. These curves are often designed as clothoids (i.e. curves where the radius of curvature decreases linearly as a function of the arc length). Theoretically, a curve transition should improve safety because it gradually leads the driver into a natural safe path on the circular curve and it provides a space for superelevation to gradually change, thus minimizing excess side friction forces. The analysis of coded studies reveals that curved roads with transition curves are associated with improved driving performance and lower crash risk. Studies have shown a significant relationship between the absence of transition curve and risk, but this relationship is dependent upon various external factors including type of terrain (level, rolling, mountainous), road width, and ADT. There is an apparent interaction between the landscape and road design elements in curves, and the application of transition curves strengthens these interactions and results in improved safety. However, the influence of transition curves on crashes is much smaller than the radius of the curve. On the basis of these results, it is expected that the measure of implementing transition curves may have analogous positive effects on road safety, dependent upon external factors.

Bendiness

Colour code: Grey

Curves are considered to be a risk factor in the design of roads. Most research on the risk of curves focuses on individual curves, only a few studies focus on bendiness. Findings from those studies are inconsistent. Two studies on bendiness report a higher risk of crashes on roads with a higher degree of bendiness and two studies found no relation, while three more recent studies report a lower risk on crashes with a higher level of bendiness. Studies reporting lower crash numbers on roads with higher bendiness hypothesise that this might be due to a better anticipation of drivers on curves. Checks are missing however whether the degree of bendiness/number of curves is related to the amount of traffic or to safety measures on more dangerous curves. Based on these findings the verdict on the effects off bendiness on crashes is therefore inconclusive. On the basis of these results, there is also no clear expectation concerning the effects of the measure of reducing the number of curves.

Densely spaced junctions

Colour code: Grey

Junction density has been identified as a risk factor although the results of research into the effect of junction density on crash frequency and/or crash severity (number and extent of injuries) is inconclusive. Some studies indicate that denser street networks with higher densities of junctions lead to fewer crashes across all severity levels. Other studies reveal the opposite with increases in the density of certain junction types leading to significantly more crashes of a certain type or of all crashes.

Alignment deficiencies - High Grade

Colour code: Yellow

The presence of steep uphill or downhill vertical grades in the road geometry, either alone or combined with horizontal curves, affects the level of road safety. This translates not only to induced accidents (both absolute numbers and frequencies), but also to increased injury severity and to speeding which has been proven to lead to accidents. A vote-count analysis was performed to capture these overall effects for high grade. On the basis of these results, it is expected that reducing gradients will have analogous mostly positive effects on road safety.

Presence of Tunnels

Colour code: Yellow

Tunnels are widely used for ease of access and locomotion. However, the presence of tunnels in road segments, either alone or combined with horizontal or vertical curves, affects the level of road safety. This translates not only to induced accidents, but also to increased injury severity and changes of the degree of lateral control which could be linked with accidents, although some results lack statistical verification. The main focus of this synopsis is the presence of tunnels affecting crashes as a primary effect (risk factor). As such tunnels are examined overall as a unit and not in depth, for instance by analysing separate design elements such as number of lanes.

Poor sight distance

Colour code: Yellow

Poor sight distance at junctions can affect road safety, as it results in other road users and/or obstacles not being detected soon enough for the driver to safely stop the vehicle. Hence, an adequate field of view is of great importance, especially when operating speeds are high. In fact most of the studies on sight distance at junctions show that poor sight distance (e.g. restriction of field of view) has a negative effect on the number of crashes, although only a few of them delivered significant results. The main approach used to investigate the effects of poor sight distance on road safety was regression analyses. Sight distance was often one factor considered as part of investigations considering a range of factors which influence road safety. One study used a driving simulator rather than real driving approach. Most research was done in Singapore, but also in the United States and China. The majority of the studies investigated junctions on urban roads.

CROSS-SECTION DEFICIENCIES – ROAD SEGMENTS

Superelevation deficiencies at curves

Colour code: Yellow

The superelevation is the right-angled slope of the road surface and is part of the horizontal curve design. Driving through a curve at too high speeds can create too high centrifugal forces causing a vehicle to skid (if the skid resistance is also too low) or to roll over. In combination with other curve design components like the curve radius and pavement friction, the superelevation decreases the risk of skidding or rolling over for vehicles driving through the curve at the design speed. Apart from reducing the risk of skidding or rolling over, the superelevation provides for water runoff. The superelevation can also increase crash risk when it is too high. It can cause vehicles too slide or roll over inwards toward the curve. The risk of such an event increases given the combination of too high superelevation rates, vehicles driving slowly, road being slippery or on combinations of horizontal curves and vertical grades. Four coded studies all found that superelevation deficiencies relate to an increase in crashes at curves. Passenger vehicles were found to be more prone to skidding than rolling over. Heavy good vehicles on the other hand were found to be prone to rolling over due to a relatively high centre of mass. Also, the studies indicated that taking operational speeds into account in the design and evaluation of curves will result in a more robust curve design. On the basis of these results, it is expected that the measure of improving superelevation will have analogous positive effects on road safety.

Number of lanes

Colour code: Red

Most of the studies show that an increasing number of lanes is related to an increase in crashes . This might be partly explained by an increase in lane changing and overtaking manouevres and speed differences between vehicles. Another relationship is that a higher number of traffic lanes relates to a higher traffic demand. This means that the relation between number of lanes and crashes is not causal. The effect of the number of lanes on crashes always concerns the number of crashes or total crash reduction, often with a distinction between crash severities. A distinction between crash types is rarely found. One study indicates a decreasing number of crashes for an increase of lanes, while the remaining studies indicate the opposite. The difference is related to other factors like annual average daily traffic (AADT), speed limits, lane width, road type and the percentage of heavy good vehicles (HGV). Most of the studies involve Crash Prediction Models (CPMs).

Narrow lanes

Colour code: Yellow

Research shows that narrow lanes can have both positive and negative effects on road safety. The effect of a narrow lane on crashes often concerns only the number of crashes or total crash reduction. A distinction between crash types is rarely found. Some studies indicate that narrow lanes lead to a higher number of crashes while other studies reveal an opposite effect. The difference depends on the circumstances and factors like annual average daily traffic (AADT), road type, shoulder width and the percentage of heavy good vehicles (HGV). Most of the studies involve Crash Prediction Models (CPMs).

Narrow Median

Colour Code: Yellow

Estimates are based on studies that examine the relationship between median width and both frequency and severity of crashes. It appears that a decrease in median width increases crash frequencies. The effect seems to be more pronounced for crash involvement of female and older drivers. However if median width is less than 40 feet (12 m) the no-injury crash rate appears to decrease. A non-significant effect on injury severity of bus crashes has been found. All studies are from the US.

Absence of paved shoulders

Colour code: Red

A road shoulder is the section of a roadway that lies immediately adjacent to the travel lane (or driven carriageway). The absence of a paved shoulder has been identified as a risk factor in studies on two-lane rural highways. Paved shoulders may increase safety by providing a recovery area for drivers who have left the travelled lane and a place for a driver to maneuver to avoid crashes. However, shoulders may increase crash risk by conflicts caused by vehicles stopped on the shoulder and by inviting higher speeds. Most studies showed that the absence of paved shoulder was associated with an increase in crashes. One study showed that although the presence of shoulders was associated with decreases in injury and property damage crashes, it was also associated with increases in fatal crashes. Another study showed that the presence of paved shoulders was associated with larger safety effects than the presence of unpaved shoulders. In general , the evidence suggests that paved shoulders reduce total and shoulder-related crashes, but the possible speed enhancing effect of (wide) paved shoulders may increase fatal crashes.

Narrow shoulders

Colour code: Red

A road shoulder is that section of roadway immediately adjacent to the travel lane. The shoulder can be surfaced or unsurfaced. The lack of adequate shoulder width has been identified as a risk factor in studies on two-lane rural highways. Paved shoulders may increase safety by providing a recovery area for drivers who have left the travel lane and they provide a place for a driver to stop a defective vehicle and avoid crashes. However, at the same time, shoulders may to some extent increase the risk of conflicts caused by vehicles stopped on shoulder and by inadvertently inviting higher speeds (wide shoulders and wide lanes lead to a generous cross section). The described effects depend not only on the presence of a road shoulder but also on the width of the road shoulder. A wider road shoulder provides the driver with more recovery area but may trigger higher speeds. Five USA studies on shoulder width were coded. All five studies showed that wider shoulders were associated with a decrease in crashes. One study also combined the variables shoulder width and the presence of shoulder rumble strips, and showed a decrease of the number of crashes. Another study combined the variables shoulder width and speed limit, and showed a decrease of crashes for an increase of the shoulder width on roads with a higher speed limit. A third study combined the variables shoulder width and lane width and showed a decrease in the number of crashes. The remaining two studies showed the single effect of shoulder width on the number of crashes. In general, the evidence is conclusive that narrow shoulders increase the number of crashes compared to wider shoulders, be it for different conditions.

ALIGNEMENT - JUNCTIONS

Interchange deficiencies- ramp length

Colour code: Grey

In general, short ramps may cause crashes because in this case the driver does not have the time to adjust the speed appropriately. Ramp length probably affects road safety, although some mixed findings were observed. The results can be differentiated between effects on crash severity and crash frequency. The studies indicate that increased ramp length leads to more serious crashes (i.e. an increase in injury severity), but the results are significant only at 90% confidence level. A meta-analysis was conducted and that revealed a non-significant overall effect at a 95% level. The impact of ramp length on crash frequency is unclear. Two studies indicated that an increase in ramp length leads to more crashes, but opposite or non-significant effects were also reported.

Interchange deficiencies - Acceleration/Deceleration lane length

Colour code: Grey

Overall, the length of acceleration and deceleration lanes was found to have inconsistent and mixed influence on road safety. It is noted that the majority of studies focused on deceleration lanes on freeway exit areas. The majority of relevant studies investigated the number of crashes, suggesting that the effect is not clear. Nevertheless, most of the recent studies indicated that increased deceleration lane length leads to more crashes (although less severe). The meta-analysis that was carried out confirmed the inconsistent findings as a non-significant effect of the overall estimate of deceleration lane length was found (applying at a 95% level. Furthermore, a meta-analysis on the basis of two studies examining the impact of deceleration lane length on crash severity suggested a non-significant effect. However, since only two studies were included in this meta-analysis, the results should be interpreted with care. In conclusion, the inconsistent findings of international literature clearly suggest that further research is needed on this topic. On the basis of these results, it is expected that increasing acceleration/deceleration lane length will have analogous unclear effects on road safety.

AT-GRADE JUNCTION DEFICIENCIES

Number of conflict points

Colour code: Yellow

The number of conflict points at junctions, which is mostly expressed through the (total) number of lanes, appears to deteriorate road safety. Studies mostly indicate that an increase of the number of lanes (and therefore an increase in the number of conflict points) tends to increase the number of crashes, or that junctions with less lanes (and therefore less conflict points) tend to have lower numbers of crashes. Furthermore, some studies show this tendency for specific types of lanes (e.g. number of left-turn lanes in right-driving countries) as well as for specific crash types (e.g. angle-crashes). However, some studies – especially for specific crash types (e.g. rear-end crashes) – show different effects. Summarizing, in general it appears that an increase of the number of conflict points tends to increase the number of crashes, however for some crash types (e.g. rear-end crashes) an additional lane which is connected with additional conflict points could nevertheless probably lead to less crashes of this specific crash type.

Risk of different junction types

Colour code: Red

Regarding the effect of the type of junction on road safety, studies mostly show that junctions with four or more arms are associated with more crashes compared to 3-armed junctions. Those effects were often statistically significant. Furthermore, studies on accident severity mostly indicated that junctions with four or more legs increase crash severity compared to 3-armed junctions. Summarizing, at junctions with more approaches/arms like crossroads (4 arms) or multiple-armed junctions (>4 arms) more crashes are likely to occur and those junctions lead to a higher crash severity compared to 3-armed junctions (T-junctions). Compared to roundabouts, intersections are associated with more crashes in general. Roundabouts can also significantly reduce the severity of crashes.

Gradient at junctions

Colour code: Red

Regarding the effect of gradient at junctions on road safety, some studies indicate that junctions with gradient are associated with more crashes compared to junctions without gradient, especially regarding specific crash types like rear-end crashes. However, some studies also show contrary results. Studies on accident severity indicate that junctions with gradient lead to a higher crash severity. This was the case for downhill approaches (high-speed crashes) as well as uphill approaches. In summary, gradients at junctions appear to have a negative effect on the number of crashes for specific crash types (especially rear-end crashes), but they tend to lead to more severe crashes (i.e. an increase to injury severity) in general.

Skewness / junction angle

Colour Code: Yellow

Regarding the risk of skewness at an intersection, it can be observed that most studies show that a skewed angle (not a right angle) at intersections leads to a higher crash frequency compared to an intersection with roads intersecting at a right angle (or close to that). Furthermore, it also appears that a skewed angle at intersections leads to more serious crashes (i.e. an increase of injury severity). In most cases the area type was not specified. Results showing these tendencies were statistically significant in most studies. However a few studies presented varied effects for specific crash types, such as rear-end crashes, although mostly not statistically significant. Thus, in general, a skewed angle at junctions appears to lead to a higher crash frequency and probably to more serious crashes. Age and road user type (truck driver) influence the effect of skewness considerably. For instance, skewed intersections can pose specific problems for older drivers because of their reduced head and neck mobility.

TRAFFIC CONTROL- JUNCTIONS

Uncontrolled rail-road crossing

Colour code: Red

From the studies identified in the international literature it appears that uncontrolled/passive rail-road crossings are associated with more crashes compared to rail-road crossings equipped with active control devices. Also uncontrolled/passive rail-road crossings lead to more severe crashes than rail-road crossings with active warning devices. Furthermore, the studies identified partly show variable effects and national specifications regarding the different control types play a role for the effects estimated in the studies as well.

Poor junction readability-Uncontrolled junctions

Colour code: Yellow

Overall, the effect of uncontrolled junctions on road safety was not entirely clear, but they can be considered risky. Some counterintuitive findings also exist in literature. More specifically, literature suggests that fewer crashes occur at uncontrolled junctions. This could be attributed to limited exposure at these areas and to the fact that part of the crashes with pedestrians that might have occurred at uncontrolled junctions actually occurred at mid-block locations, because pedestrians choose to cross before reaching a junction. On the other hand, it was found that crashes at uncontrolled junctions tend to be more severe, but not always when crash types are examined separately. A vote count analysis that was carried out on the basis of eight coded studies confirms this tendency. It is noted that most of literature explores the effect of various traffic control measures of junctions on safety rather than the risk of uncontrolled junctions.

Absence of road markings and crosswalks

Colour code: Grey

Regarding the effects of absence or presence of road markings in general and crosswalks in particular on road safety, it can be observed that some studies indicate that more crashes are likely to occur at intersections where road markings (mainly motor vehicle crashes) or crosswalks (mainly crashes with pedestrians) are absent. Other studies, however, show contrary results. Studies on accident severity mainly show a (significant) higher injury severity at intersections without markings or crosswalks. Thus intersections without road markings and crosswalks might lead to more severe crashes in urban as well as in rural settings.

Appendix B Road Safety Measure Abstracts

EXPOSURE

2+1 roads

Colour code: Light Green

This concerns implementing a 2+1 road design on previously two-lane roads, i.e. a road design with three lanes, where the middle lane alternates as a passing lane for the two opposing directions. 2+1 roads with median barrier (cable) are found to reduce the rate of severe and fatal injuries by about 51-63 %, depending on the road type and speed limit. However, the effect on less severe injury rates is smaller and in some cases not statistically significant. This finding occurs when the measure is implemented at previously wide two-lane roads (13 m) and when narrow roads (9m) are widened at certain sections to allow for the alternating passing lanes. Implementation of 2+1 roads without a median barrier appears to reduce the number of crashes, but this might vary between road types. The reviewed studies are limited in number and most do not control for relevant confounding factors, so the results should be interpreted with care.

HGV Traffic Restrictions

Colour code: Green

HGV traffic restrictions can be defined as restrictions to lanes, speeds, times or height. In this synopsis, relevant studies were only found for HGV lane restrictions (e.g., HGV prohibited from certain lanes on a multi-lane road). These restrictions can affect road safety positively by improving traffic flow and reducing HGVs overtaking. HGV lane restrictions were investigated by analysing the results of four studies, two before-after studies, one meta-analysis and one simulation study to identify whether these restrictions affect vehicle speeds and/or accident numbers. The results found that, overall, HGV lane restrictions did result in reduced speeds and accident numbers, and in most studies, the results were statistically significant, including on the restricted lane and adjacent lanes. And where results were not significant or significance was unknown, reductions in accident rates and speeds were still seen. This topic has been studied across a limited number of conditions and countries (USA only), so the transferability of the results will be limited. However, overall the results did not show any increases in vehicle speeds or accidents, which indicates that HGV lane restrictions are overall an effective safety measure.

INFRASTRUCTURE SAFETY MANAGEMENT

Road safety audits & inspections

Colour code: Light Green

Road safety audits and inspections are conducted commonly by experts to highlight problems and deficiencies in a road or network for further consideration and examination by road management authorities. They are tools that enable secondary measures to be determined and applied. Five high quality studies were coded, and a meta-analysis based on the results of two of them was conducted. Results indicate a significant crash reduction of 60% after implementing the audit tool, hinting at considerable bonuses that stand to be gained from more widespread use of road safety audits. On a basis of both study and effect numbers, it is evident that road safety audits and inspections can create positive impacts on road safety by reducing crash and injury numbers. In a minority of cases their impact is inconclusive or has isolated negative effects. The results seem generally transferable with caution.

High risk sites treatment

Colour code: Light Green

High risk site treatment measures are screening processes, commonly implemented to highlight problematic locations in a road or road network, for further consideration and examination by road safety experts. They enable secondary measures to be determined and applied, and hence improve road safety as a result of their targeted nature. Four high quality studies were coded, including two meta-analyses. The two meta-analyses encompass several effects, and show statistically significant reductions in injury crashes of 28% and 24% to 27%. On the basis of both study and effect numbers, it is evident that high risk site treatment has a positive impact on road safety by reducing crash and injury numbers. The results seem generally transferable with caution.

Reduction of speed limit

Colour code: Green

In the context of road transport, various speed limitations have been used worldwide, depending on historical background, infrastructure, country system of units, etc. It has been demonstrated that the faster vehicles go, the worse accidents are: increased crash risk, increased severity, and increased fatality rate. In that context, a meta-analysis from 2013 was analysed as well as five other more recent studies in order to evaluate the impact of speed limit reduction on road safety. Speed limit reduction measures were found to have a positive impact on road safety. Speed limit reduction reduces average speed on the road which has positive effects on road safety. The meta-analysis predicted a strong exponential link between relative injuries/fatal crash risk and initial speed. That means that speed decreases on highways would have even larger positive effects than speed decreases from 50 km/h. No evidence was found of negative effects on crash rates, or (fatal) injuries. The synopsis also highlights that the effects of speed limit reduction can change as a function of the road section that is considered: there seem to be smaller effects on intersections than on the road sections. But the meta-analysis illustrated that, overall, speed limit reduction had positive effects on road safety everywhere in the studied countries. This synopsis concludes that speed limit reduction can be considered as an important measure to improve road safety, but also that more studies should include statistical analyses in order to confirm all these trends.

Dynamic Speed Limits

Colour code: Green

Dynamic speed limits (DSL) are limits that change according to real-time traffic, road or weather conditions. In DSL schemes road users are typically informed of speed limit changes by electronic signs that are housed within gantries situated above the lanes. DSL systems are increasingly applied worldwide, usually on motorways. One of the objectives of DSLs is to improve traffic safety through reductions in mean speeds and in speed variations within and across lanes, and between upstream and downstream flows.

The number of studies on the safety effects of DSLs that have been published in peer-reviewed journals is limited. Moreover, they are sometimes difficult to compare with each other as multiple research designs were used, and not all studies evaluated DSLs that operate in comparable conditions. The reviewed studies report favourable road safety effects. The only available before and after study reports a significant reduction of 18% of injury crashes due to the presence of a DSL system. The observed reduction is mainly attributable to a reduction of rear-end crashes. Some other studies evaluated the effects of DSL on driving speeds, and reported decreases of mean speeds as well as reductions of speed variances.

Apart from affecting traffic safety, DSLs could also have effects on traffic flow, congestion and travel times, as well as on vehicle emissions and road noise. Nevertheless, no conclusive effects on any of these outcomes were found in previous implementations and experiments.

One cost-benefit analysis showed a benefits-to-costs ratio of approximately 0.7 for a DSL system, which means that the costs might exceed the benefits.

Little is actually known about possible conditions that could influence the effects of DSLs. It is likely that the impacts of DSLs are sensitive to the level of driver compliance. As the level of driver compliance tends to vary across jurisdictions, results of DSL schemes are not necessarily transferable from one jurisdiction to another.

Dynamic Speed Display Signs

Colour code: Green

Dynamic speed display signs (DSDSs) measure the speed of approaching vehicles and communicate the vehicle's actual speed to drivers on a digital display along the road, possibly also including pictures or verbal messages such as "Slow down" or "Thank you". The underlying idea is that DSDSs help motorists self-enforce their speed. DSDSs should not be confused with dynamic speed limits (DSLs) which can impose different speed limits depending on traffic or weather circumstances. The essence of DSDSs is the individual feedback on driven speeds.

The number of studies on the effects of DSDSs published in peer-reviewed journals is limited. Most evaluations have been done by means of before-and-after studies, focusing rather on the resulting speed behaviour than on the (indirect) effect on crashes. No meta-analyses were found.

All reviewed studies consistently report significant decreases of mean speeds due to the presence of active DSDSs, although the size of the effect differs. The observed mean speed decrease ranges from 1km/h to 10 km/h. The observed decreases of the 85th percentile speed are of the same magnitude. The results of all the studies appear to be relatively homogenous which suggests that the measure is reasonably well transferable to other similar settings, including those in other countries.

All studies also evaluated the proportion of drivers who exceeded the speed limits by some amount and reported considerable reductions in the highest exceedances of the speed limits. Some studies concluded that drivers become less responsive towards the DSDS over time, but the most elaborate study did not find significant evolutions in mean speeds at the DSDS locations during the period of use. All studies agreed that the speed reductions observed while the DSDSs were in place disappeared after the devices were removed from the study sites. It was also found that drivers increase their speed again after passing the DSDS. DSDSs that extend the numeric feedback with verbal messages tend to outperform the ones with only numeric feedback.

One study calculated the effect on the number of crashes and found a significant overall reduction of 5%.

Installation of section control & speed cameras

Colour code: Green

Section control and fixed speed cameras aim to reduce the number of crashes by enforcing the sign-posted speed limits. While fixed speed cameras measure the driving speed at one specific point, section control measures the average driving speed over a longer road section.

Most research regarding speed cameras and section control suggests a favourable impact on road safety. Section control was found to significantly reduce the number of crashes in a meta-analysis that was published in 2014. The estimated reduction in the number of crashes is somewhat stronger than for fixed speed cameras: -30% for the total number of crashes and -56% for crashes involving killed or severely injured victims. These results were confirmed by three more recent papers. Some indications are found of favourable spillover effects to non-treatment sites further downstream.

Results from the same meta-analysis indicate that fixed speed cameras significantly reduce the total number of crashes by about 20%. The results are to some extent confirmed by three more recent papers. The results suggest that the effect is very local, and no indications of spillover effects to non-treatment sites were found. A stronger effect was found for fatal crashes (-51%), but this could partly be explained by regression to the mean.

Implementation of 30-Zones

Colour code: Green

30km/h (or 20mph) zones are found mainly in residential and urban areas. They aim to reduce vehicle speeds, often using physical speed reducing measures to further encourage slower driving. This improves safety for all road user types. The effects of implementing 30km/h zones were investigated by analysing the results of five before-after studies to identify whether these zones affect vehicle speeds, accident and casualty numbers. The results show that 30km/h zones result in reduced speeds and reduced number of accidents and casualties. In two of the five papers, the results were statistically significant. Significant results were also found when looking at specific groups of accidents and road user types. 30km/h zones were found to be not as effective in reducing speeds and accidents if it was not combined with other structural measures. This implies that 30km/h zones only work effectively if physical speed reducing measures are implemented alongside the reduced speed limit. This topic has been fairly well studied, but not across many different countries, and not always using statistical analysis, which limits the transferability potential of the results. However, overall the results did show reductions in speeds and accidents/casualties, which indicates that 30km/h zones are an effective safety measure.

Installation of Speed Humps

Colour code: Green

Vertical speed deflection devices (known in general in this study as 'speed humps') aim to reduce vehicle speeds, particularly in urban and residential areas, and to improve the safety not only for vehicles, but also for pedestrians and cyclists using these areas. The effects of the installation of speed humps and other similar devices were investigated in the six studies selected for this synopsis (including one meta-analysis). Studies used either accident rate or vehicle speeds to measure the effectiveness of speed humps. The results found that the installation of speed humps and other similar devices reduces accident rates and vehicle speeds, sometimes significantly. These significant results were found specifically with speed humps and raised crossings, although non-significant decreases were also found with speed bumps and cushions. The topic has been investigated in a relatively wide range of countries and looking at a number of different road user types, but has not considered other condition types (e.g. transport modes…), which limits the transferability potential of the results slightly. However, even when considering this, speed humps appear to be an effective safety measure.

Implementation of Woonerfs

Colour code: Grey

Woonerfs are a concept originated in the Netherlands and are areas which are designed to meet the needs of pedestrians and cyclists and encourage slow speeds from motorised vehicles, making it a safe and pleasant place to be. They are also known as Home Zones, Complete Streets and can also include shared space. The effects of implementing woonerfs and similar schemes were investigated by analysing the results of five before-after studies to identify whether the introduction of these schemes affect accident rates and speeding vehicle rates. The results found that implementing Home Zones and Complete Streets did overall lead to reduced accident and speeding vehicle rates. However , the results for the shared space schemes were more mixed, with some increases in accident rates being seen at specific sites, as well as reductions at other sites. This implies that shared space is not always successful in reducing accident rates in all locations. However, no statistical analysis was undertaken in any of the post-1990 studies, so it is not known whether these results are significant. This topic has only been studied across a limited number of conditions and countries, so the transferability of the results will be limited.

Implementation of narrowings

Colour Code: Light Green

Road narrowings, perceptually and/or physically, aim to reduce vehicle speeds. Five studies were selected as appropriate for inclusion in the synopsis of the measure "implementation of narrowings", including two before-after study and three simulator studies. Across the five studies, differences in speed data (five studies), accident rates (one study) and deceleration distances (two studies) before and after the implementation of road narrowings were analysed using statistical analysis. The results across all five studies showed that the implementation of perceptual and/or physical road narrowings reduces accident rates, vehicle speeds, and speeding vehicle numbers, and increases deceleration distances (i.e., drivers starting to decelerate further away from the intersection/crossing). Where available, significant positive results were found for accident rates, mean speeds, minimum speeds during deceleration and deceleration distances. However, the only study which analysed accidents included other measures, such as speed-activated signs, so it is not clear to what extent the reduced accident rates were due to the implementation of the narrowings. This topic has been studied across a limited number of conditions and countries, so the transferability of the results will be limited. In general. lower speeds have been shown to result in lower accident rates, so based on the speed results, it is likely that there are safety benefits to implementing narrowings.

Implementation of Traffic Calming Schemes

Colour code: Light Green

Traffic calming schemes aim to create an area of roadway where reduced vehicle speeds are encouraged by the use of an array of speed reduction measures (e.g., speed humps, chicanes,..). This way they not only aim to improve safety for vehicles, but also for pedestrians and cyclists. The effects of installing traffic calming schemes were investigated using three meta-analyses (10, 16 and 33 studies respectively) and one further before-after study. Studies used either accident or casualty rate to measure the effectiveness of installing traffic calming schemes. The results showed that their implementation reduced accident rates and casualty rates to a significant level, particularly when looking at accident and casualty rates overall. Significant results were also found for specific groups of accidents or casualty types (e.g., drivers over 25, single vehicle crashes, local/main roads), but not for others (e.g., pedestrian crashes, fatal casualties, drivers under 25 years). The topic has been fairly well studied across a number of European countries and in Australia, but most studies were rather dated (1980's/1990's), which limits the topic's transferability potential. However, overall ,traffic calming schemes appear to be an effective safety measure.

School zones

Colour code: Light Green

A school zone refers to a road area near a road traffic network around a school that has a likely presence of (young) pedestrians. In general, school zones have a reduced speed limit during certain hours. Most studies on the road safety impact of school zones used before and after measurements of vehicle speeds in these zones as the safety relevant indicator. There is evidence that a lowered speed limit in a school zone can substantially reduce vehicle speeds, but nevertheless vehicle speeds tend to remain far above the posted speed limit. There is evidence that speeds in school zones may be reduced by the application of speed monitoring displays and fiber-optic signs. The speed-reducing effects of speed monitoring displays have also been found to remain stable at long term. Studies have not consistently demonstrated that flashing beacon signs or pavement marking significantly reduce vehicle speeds in school zones. The presence of specific elements in the physical road environment (sidewalk, crosswalk, pedestrian fencing) may contribute to lower speeds in school zones. The research evidence is not clear on how the length of school zones and number of lanes affect vehicle speeds: opposing results have been found.

ROAD TYPE

Creation of bypass roads

Colour code: Green

International studies indicate that the installation of a bypass road, which leads non-local (through) traffic around a town or business district, reduces traffic accident rates on both the new and the old roads. The decrease in the overall accident rate varies between 19% and 66%. However, most before-after studies did not meet the requirements of a good before-after design: a selection bias may be present in the studies which may have led to some overestimation of the intervention effects. In general, safety effects of bypass roads are expected to be greater when the old road through town has a relatively high accident rate, when more traffic is shifted to the bypass road, when no extra traffic to either the old or the new road is generated, when speed-reducing measures are used to control for possible increases in speeding on the old road network, and when intersections between the old and new bypass road have a safe design. The general principle that bypass roads can lead traffic away from roads with a relatively high crash rate makes it a road capacity/road safety measure that will be effective in and transferable to most traffic conditions.

ROAD SURFACE

Road surface treatments

Colour code: Light green

Road surface has to be maintained in such way that it enables secure traffic. Road surface treatments are methods for extending the lifetime of deteriorating road pavement. Well-maintained road surfaces with adequate skidding resistance help to minimize traffic accidents. The relationships between road surface characteristics and crash occurrence have been established in a number of studies. This synopsis deals with improving friction, resurfacing and winter maintenance which are important surface characteristics with regard to safety.
Across all four coded studies, results have highlighted that road surface treatments have positive influence on road accident reduction. But the two meta-analysis shows that resurfacing does not appear to cause statistically reliable changes in accident numbers.

LIGHTING

Installation of lighting & Improvements to existing lighting

Colour code: Green

The aim of the installation of road lighting and improvements in existing road lighting is to increase visibility, mostly to help reduce nighttime crash frequency. A meta-analysis is available that covers both the installation of road lighting and improvements in existing road lighting (Høye, 2014).
Based on the combined results of 53 individual studies, the meta-analysis shows that the **installation of road lighting** significantly reduces the number of fatal crashes in the darkness by 52%, and the number of injury and unspecified crashes in the darkness by 26%. Fatal pedestrian crashes in the darkness decrease by 78%, while pedestrian injury crashes in the darkness decrease by 51%. The effects of installation of road lighting are generally larger for fatal crashes than for less severe crashes, and more favourable for crashes involving pedestrians than for other types of crashes.

Based on the results of 26 studies, the meta-analysis indicates that **improvements to existing road lighting** generally have a favourable effect on road safety as well. Increasing the lighting by two to five times the previous level reduces the number of injury crashes by 13%. Increasing the lighting to five times the previous level or more reduces injury crashes by 32%. A reduction of the lighting level to half of the previous level was found to significantly increase the number of injury crashes by 17%. Three more recent papers on changes to existing road lighting were coded that showed mixed results and could therefore not confirm the results of the meta-analysis.

In general, it can be concluded that the vast majority of research available suggests that both installation of and improvements to road lighting have a **favourable effect on road safety**. The effect on crashes of improving existing road lighting seems smaller than the effect of installing road lighting on previously unlit locations. It also seems that improvements to existing road lighting need to be quite strong (more than doubling the previous level of lighting) in order to have a significant effect on the number of crashes. Transferability of the results may, however, be somewhat uncertain due to the substantial differences in effect size that were found in different studies. Some evidence suggests that effects differ between different types of road users and types of locations.

WORKZONES

Workzones: Signage installation and improvement

Colour code: Green

Workzone measures such as signage installation and improvement are commonly implemented to warn drivers of their transition into a more unfamiliar and unpredictable environment where construction is taking place. Their presence impacts road safety levels, reducing vehicle speeds and improving lane keeping. Five high quality studies regarding various workzone measure implementations were coded. On a basis of both study and effect numbers, it can be concluded that workzone signage creates mostly positive impacts on road safety. There were cases, however, that showed opposite results, indicating decreases in speed limit compliance rates. However, these were farther from the working sites and therefore less reliable. The results seem generally transferable with caution.

CROSS-SECTION – ROAD SEGMENTS

Increase number of lanes

Colour code: Grey

The number of lanes is an element of the cross-section of a road. It is determined by expected traffic volumes, traffic composition and design speed. Conversions to a higher number of lanes have often been undertaken to manage higher traffic volumes and improve the traffic flow. On theoretical grounds safety benefits can be expected. Multiple-lane roads provide continuous opportunities for safe overtaking and can therefore have a positive effect on traffic operations by decreasing the interactions between faster and slower vehicles. However, increasing the number of lanes may also increase same-direction conflicts and can lead to an increase in driving speeds. It also increases the crossing distance for crossing traffic (including pedestrians and cyclists). The effects of changing the

number of lanes on road safety depends on a number of closely interrelated factors, including Average Daily Traffic (ADT), paved width, roadway type, and cross-section elements.
For both urban and rural roads, conversions of undivided two-lane roads to divided four-lane roads have been found to result in substantial accident reductions. But these large reductions are due to both the change in number of lanes and the physical separation of opposite lanes. The evidence concerning the conversion of 2- lane to 4-lane undivided rural roads is mixed. Depending upon ADT, results may be more or less positive. On high volume roads the conversion is associated with safety benefits, but not on lower volume roads. The evidence concerning the conversion of 4-lane or 5-lane roads to 5 or 6- lane roads indicates that road safety is not improved or may be negatively affected.

Increase lane width

Colour code: Grey

Lane width is one of several important variables of the cross-sectional road design. Cross sectional elements such as lane and shoulder width vary depending on roadway function, traffic volume, and design speed. According to the geometric design manuals, higher traffic volume and design speed require wider lanes and shoulders.
The findings or processes concerning lane width that are transferable to or operative in all countries are that narrow lanes invite lower speeds and have a higher risk of same or opposite direction contact between vehicles, and that wider lanes invite higher speeds and a lower risk of same or opposite direction contact between vehicles. Also a more general finding corroborated in various studies is that on two-lane rural or urban roads the widening of lanes tends to improve road safety.
For rural two-lane highway roads there is robust evidence that increasing lane width reduces the occurrence of single vehicle run-off-road same and opposite direction crashes. However, at the same time studies have indicated that very wide lanes (or shoulders) may increase crash risk mainly due to higher speeds. American experts have agreed upon crash modification factors for lane and shoulder widths in the Highway Safety Manual. Some studies in the USA show road safety benefits by decreasing lane width whereas others show negative effects. For roads with 3.65 metre lanes and with speed limits of 40 mph (around 65 km/h) or higher it was estimated that decreasing lane width would produce better safety results than increasing lane width. Other studies in the USA show that adding a lane by narrowing existing lanes on four-lane urban freeways may increase accidents. These conflicting results illustrate the importance of looking at combinations of cross-sectional elements rather than trying to isolate one specific element.

For those roads in Europe which are similar to the studied American roads in terms of main design variables such as speed limit, lane width, number of lanes, shoulder width, traffic volume and lane separation, the results from American research may be used as a valid reference.

Installation of median

Colour code: Light Green

A median is a physical separation between opposing traffic streams. Results of the studies on the effects of the installation of medians on road safety indicate that the installation of medians significantly reduces injury crash occurrence by 8% on two-way roads. The effect is greatest on urban roads and on control-access roads like motorways (roads with no level intersections). However, installation of medians at intersections is found to increase accidents by 50%. Unfavourable effects of median installation have also been found in curves and when medians imply narrower lanes. Most research was carried out in the United States, Australia, Denmark, Norway, Germany and Malaysia.

Increase median width

Colour code: Light Green

Median width is defined as the width of the portion of road separating the travelled ways for traffic in opposite directions, including the inside shoulder. Overall, since one study and a meta-analysis including several studies were found, the topic has been studied to a sufficient extent. The effect of median width has been measured through accident frequency. Roads with wider medians in general have fewer accidents than roads with narrower medians. At road segments, this effect is small but significant. The effect of increasing the median width in intersections with 1m is not statistically significant. Intersections with a median wider than 2m have more accidents than intersections with a median of less than 2m. Increasing the median width appears to reduce the number of car accidents as well as the number of bike accidents at two way roads on urban and rural roads. All the research was carried out in the United States with one European study (meta-analysis) found, based on several studies.

Change median type

Colour code: Light Green

Median barriers are physical separations for opposing traffic streams and help stop vehicles travelling onto opposing traffic lanes. Median barrier treatments usually have a positive effect on road safety reducing the number of crashes. Apart from crash reductions, reduced crash severity has been associated with median barrier treatments. Results of the studies focusing on the effects of median barrier treatments on road safety indicate that beam median barrier treatments appear to significantly reduce fatal accidents by 87% and accidents of unspecified severity by 91% for "crossing the median" type of accidents. However, it is associated with a 73% increase in accidents of unspecified severity, for in median (without crossing) type of accidents. Most research was carried out in the United States, United Kingdom and France. Studies from France and the United Kingdom were included in the Norwegian meta-analysis whereas the only additional study was from the United States.

Increase shoulder width

Colour code: Light Green

Increasing shoulder width relates to increasing the space available to drivers to perform an emergency stop or to recover the vehicle in case of an error. Results of the studies focusing on widening shoulders on road safety indicate that increasing the shoulder width significantly reduces crash occurrence. However, under specific circumstances when considering shoulder related crashes, increasing shoulder width may lead to an increase of accidents (e.g. fatal shoulder related accidents on rural roads). Transferability is questionable since all studies identified were carried out in the United States.

Change shoulder type

Colour code: Grey

Results of the studies focusing on the effects of "change shoulder type" on road safety indicate that changing shoulder type from unpaved to paved significantly reduces crash occurrence, thereby having a positive effect on road safety. However, changing shoulder type from unpaved to paved shoulder was negatively effective for fatal and injury accidents on shoulder width greater than 2.44m on rural interstate roads, for fatal accidents on shoulder width of 1.83m on rural two-lane roads, for fatal accidents on shoulder width of 2.44m on rural two-lane roads, for fatal accidents on shoulder width > 2.44m on rural two-lane roads, and for injury and damage only accidents on shoulder width >2.44m for urban interstate roads. All the research was carried out in the United States.

Implementation of rumble strips at centreline

Colour code: Green

Rumble strips are rows of raised pavement markers placed along or adjacent to a road's edgeline or centreline. Centreline plus shoulder rumble strips have been shown to reduce the frequency of crashes on road segments. Results for centreline rumble strips: head-on collisions, running off the road on the left side, side-impact collisions with vehicles in the oncoming lane on the left hand side, which are the target accidents, showed a 37% reduction. Results for centre- and edgeline: head-on collisions, running off the road on either side, side swipe accidents between vehicles travelling in opposite directions showed a 32% reduction. The presented results are for all accident severities as no differences were found for different degrees of accident severity. No differences were found for studies with and without control for regression to the mean. The results do not seem to be affected by publication bias, and do not contain significant heterogeneity, with the exception of edge- and centreline rumble strips for all accidents.

Safety barriers installation - change type of safety barriers

Colour code: Light Green

Roadside barriers are widely used as safety devices to mitigate the effects of crashes and to avoid run-off-road accidents, containing vehicles and redirecting them back to the carriageway. The presence of safety barriers results in a reduction of severe crashes (i.e. fatal, serious, slight injury). Six high quality studies regarding various safety barriers installations and replacement were coded. On the basis of both study and effect numbers, it can be argued that safety barriers create positive impacts on road safety. One meta-analysis reported significant fatality increases, and mixed results for injuries. Three other studies reported mostly significant decreases in crash frequency, while another claimed a reduction in crash severity without statistical verification. No significant effects were found on driving speed and lateral position, while mostly positive effect on several test indices (notably, Acceleration Severity Index, Theoretical Head Impact Velocity, and Post-impact Head Deceleration) were found, but no statistical data were provided.

Increase widht of clear-zone

Colour code: Light Green

The roadside clear zone is the distance from the edge of the travel lane which should be free of any non-traversable hazard such as steep slopes or fixed roadside objects. Increasing such distance might help the drivers to recover their vehicle in case of running off the road and improve visibility conditions. An increase of the width of a clear zone from around 1 metre to around 5 metres seems to decrease crash occurrence by 22%. Increasing the width from around 5 metres to around 9 metres has been found to reduce crashes by 44%. The results derived from a meta-analysis based only on two studies. Moreover, it is unknown whether the results also include the effects of other associated improvements such as improved sight conditions along the road. No details are available on whether these results apply to urban or rural areas.

Installation of chevron signs

Colour code: Green

Chevron signs are widely used as safety devices to warn drivers of a dangerous curve by delineating the alignment of the road around that curve. Therefore, the presence of chevrons, either alone or combined with other devices, affects the level of road safety. Chevrons cause a reduction in the number of crashes and in driving speed, and have beneficial effects on lateral position. Seven high quality studies regarding various chevron sign implementations were coded. On the basis of both study and effect numbers, it can be argued that chevron signs have positive impacts on road safety. However, there were isolated cases where contradictory results were seen, indicating increases in speed. The results seem generally transferable.

Implementation of edgeline rumble strips

Colour code: Light Green

Edgeline rumble strips are used to alert inattentive drivers of potential danger by causing tactile vibration and audible rumbling, transmitted through the wheels into the vehicle interior. Five high quality studies regarding different implementations of edgeline rumble strips were coded. Their presence has an impact on road safety levels, causing a reduction in the number of total crashes and the number of encroachments across the edgeline. In most cases the reductions are statistically significant. Additionally, implementation of rumble strips leads to an improvement in vehicular lateral position. No significant effects were found for severe crashes and passing manoeuvre indicators. On the basis of both study and effect numbers, it has been found that rumble strips create a mostly positive impact on road safety, but the results are not always consistent. Results are transferable with caution.

Cycle lane treatments; cycle path treatments

Colour code: Grey

Cycle lanes are a protected space for bicycle traffic on the carriageway while cycle tracks are lanes physically separated from the carriageway. The implementation of cycle lanes usually has a non-significant positive effect on road safety; reducing the number of accidents, not only cycle accidents, but the total number of accidents. The implementation of cycle tracks on the contrary has a non-significant effect in reducing collisions between cyclists and motor vehicles and may increase the total number of accidents, particularly road accidents at intersections, having therefore, a significant negative effect on road safety. The main results are based on two meta-analyses.

TRAFFIC CONTROL– ROAD SEGMENTS

Variable Message Signs

Colour code: Light Green

Variable Message Signs (VMS) are electronic traffic signs that can be used to deliver various messages to passing drivers, such as warnings for adverse weather conditions, incidents, congestion or roadwork zones. Various studies were identified that investigated VMS. However, most studies investigated drivers' behavioural adaptations to the VMS rather than the effect on crashes.

Only one study looked into the effects of VMS on crashes. The results were mixed; a comparison of road sections with VMS and without VMS showed no significant results, but a comparison of sections with VMS active, versus inactive, showed a significantly lower crash rate when the VMS were active.

Other studies looked into the behavioural effects of VMS, either on the road or in a driving simulator experiment. Several studies found that VMS significantly reduce driving speed. There were indications that the impact of VMS on driving speed might somewhat reduce over time. There are also indications that the deviation in driving speed could increase when VMS are in operation. VMS location and information format appear to have a major influence on the resulting behavioural adaptations of drivers.

In general, it can be concluded that VMS significantly affect drivers' behaviour. When used in the right conditions and using appropriate messages, VMS could contribute in a positive way to road safety.

Traffic sign installation; traffic sign maintenance

Colour code: Green

Traffic signs are widely used to warn road users and provide them with information. Their presence and effectiveness affect road safety levels, causing a reduction in mean speed and in the number of vehicles travelling over the displayed speed limit. In addition to this, traffic sign installation and maintenance also lead to an improvement of vehicular lateral position. Five high quality studies regarding various traffic sign installation and maintenance were coded. On the basis of both study and effect numbers, it can be argued that traffic sign installation and maintenance has positive impacts on road safety.

Vehicle to Infrastructure (V2I) schemes

Colour code: Grey

Vehicle to Infrastructure (V2I) schemes use real-time two-way communication between vehicles and infrastructure with the goal of realizing safety, mobility, and environmental benefits. Examples of reported applications include stop sign violation warning, railroad crossing violation warning, real-time weather information, oversize vehicle warning, and incident and congestion warning. Most of the applications are currently in a state of development with sometimes not more than prototypes and trial versions available. The amount of available sources for summarising study results is therefore currently still very limited. With a growing number of applications it is likely that this number will increase during the next few years. However, at present no meta-analyses or even no comprehensive real-world evaluation studies are available. The available study results show that V2I-measures have some potential to reduce crash risks as they may affect some indirect safety indicators, but too little is known about the eventual outcomes on the level of traffic safety. Due to the heterogeneity of applications, results will not necessarily be transferable from one V2I system to another.

ALIGNEMENT - JUNCTIONS

Convert at-grade junction to interchange

Colour code: Green

At-grade junctions are intersections where two or more roads meet at the same level. This means that a regulation of junction space-time is required, either by default right-of-way regulations or by traffic signs and signals at the junction. Vehicle paths and directions intersect with each other. This not only leads to increased delays due to junction capacity (only specific directions may use the junction area at any given time), but also to an increased road safety risk due to the crossing of paths of road users. Road safety and traffic flow can be improved by separating those directions and eliminating the relevant conflicts via the introduction of segregated pathways for traffic, realised by the construction of height-separated junction arms. A level junction is thus converted to an interchange, and vehicles can traverse without conflicts. Three high quality studies, two of which were meta-analyses, including various conversion treatments were coded. The outcomes usually expressed crash reduction in terms of either the absolute difference between crash numbers, or the percentage change before and after the conversion. Usually there were no outstanding modifying factors due to the nature of the measure. However, in one case lane addition took place simultaneously as well. On a basis of both study and effect numbers, it can be argued that converting at-grade junctions to interchanges has a positive impact on road safety. Some cases reported non-significant results, but these were isolated. The results seem generally transferable.

Convert 4-Leg-Junction to Staggered Junction

Colour code: Light Green

From the studies identified in the international literature, it seems that the conversion of 4-leg junctions to staggered T-junctions statistically significantly reduces injury crash occurrence, especially when the amount of side road traffic is relatively high. However, converting 4-leg junctions to staggered T-junctions when the amount of side road traffic is low, appears to significantly increase injury as well as property damage only crash occurrence. Even though positive effects in general are seen for converting crossroads to staggered T-arms, negative estimates might appear when it comes to different road networks, traffic demand or crash types. One European meta-analysis was included, other research was mainly carried out in the United States and Australia. Therefore, the transferability may be questioned because of potential regional characteristics.

Installation of railroad crossing traffic signs

Coulour Code: Light Green

Results of the studies focusing on the effects of the installation of railroad crossing traffic signs (at previously unprotected and unsigned railroad crossings) on road safety indicate that the installation of stop signs significantly reduces crash occurrence by 65% and also has positive effects on driver behaviour. However, stop signs were negatively effective at crossings with higher train speeds (e.g. train speed higher than 30 mph - 48 km/h). Other types of specific warning signs (e.g. hazard warning signs or highly reflective warning signs) seem to significantly reduce crash occurrence as well. In addition to one European meta-analysis, most research was carried out in the United States and is probably linked with national specifications. These national specifications are especially relevant for this topic because traffic signs at railroad crossings differ between countries and there are several specific traffic signs used.

Improve skewness or junction angle

Coilour Code: Grey

From the studies identified, it seems that the improvement of skewness or junction angle, i.e. junction angle realignment, might reduce crash occurrence and have positive effects on driving performance. As presented in one study, the improvement of junction angle benefits both older (65-85 years) and younger drivers (25-45 years). However, since none of the effects were statistically significant and also a (non-significant) increase in crash occurrence for specific crash types, e.g. head-on turn crashes, was observed, it is difficult to make general statements on the effects of the improvement of skewness or junction angle on road safety. Research focused on crashes involving motor vehicles. Moreover, it was only carried out in the United States; hence, findings are probably influenced by national specifications.

Channelisation

Colour Code: Green

From the studies on the effect of channelisation of junctions on road safety, it seems that channelisation of junctions reduces accident frequency: most studies reported reductions in accident frequency that were statistically significant. Although some negative effects were presented in some studies, these were not statistically significant. Since the results regarding specific outcomes are diverse, differences between the effectiveness of left-turn lanes and of right-turn lanes or between T-arms and crossroads are difficult to quantify. Research was mainly carried out in North America as well as in China and Australia. The transferability may be questioned because of potential regional characteristics.

Convert junction to roundabout

Colour Code: Light Green overall
Grey for cyclists

From the studies on the effects of the conversion of junctions to roundabouts on road safety, it appears that applying this treatment reduces fatal and injury accident frequency (especially in rural areas). An exception are accidents involving cyclists for which safety effects vary strongly according to the type of cyclist facility: whereas roundabouts with cycle lanes seem to increase bicycle accidents, for roundabouts with cycle paths reductions of bicycle accidents can be seen. Moreover, the conversion of junctions to roundabouts might lead to only small improvements and, in the case of multi-lane roundabouts, even increases damage only accident frequency. Roundabouts are also more effective on roads with a higher speed limit. The transferability of the results would appear good, as studies from many different countries were included.

Sight distance treatments

Colour Code: Green

From the studies on the effect of sight distance treatments on road safety in the literature (including one meta-analysis), it appears that in general sight distance improvements reduce crash occurrence. Moreover, studies show that measures for improving sight conditions (e.g. visual warning systems) can have positive effects on road user behaviour, e.g. a decrease in driving speed, whereas similar effects are possible with intended sight obstructions. Different kinds of warning signs were tested: (1) vehicle-activated warning signs and (2) standard static signs. Modifying effects regarding drivers' age were not found. As most of the studies were carried out in the United States, the transferability might be problematic. However, a European meta-analysis was included.

TRAFFIC CONTROL- JUNCTIONS

Automatic barriers installation at rail-road crossings

Colour Code: Green

Regarding the effect of the installation of automatic barriers at railroad crossings on road safety, it appears that the installation of automatic barriers at railroad crossings is associated with a reduction of crash occurrence, especially at railroad crossings that previously only had warning signs. Moreover, it seems that the installation of automatic barriers also has positive effects on driver behaviour at railroad crossings and might reduce violations. The effects of the installation of barriers seem to be consistent when it comes to different road networks, et cetera. In addition, studies were drawn from Asia, Europe, America as well as Australia enabling good transferability of results.

STOP/YIELD signs installation or replacement

Colour code: Grey

Regarding the effects of the installation or replacement of stop/yield signs at junctions on road safety, it can be observed, that only the installation of two-way stops and four-way stops significantly reduces crash occurrence. For the installation of one-way stops only non-significant results were presented. This applies also for installing yield signs. The replacement of stop signs by yield signs, however, seems to significantly increase crash occurrence. Research mainly focused on crashes with motor vehicles or did not differentiate between road user groups or traffic volume. Most research was carried out in Australia, but a European meta-analysis (from Norway) was found as well. In general, the coded studies are of sufficient quality and are methodologically sound.

However, some studies did not consider changes in traffic volume, and regression to the mean appears to be a problem in some studies.

Implementation of marked crosswalks

Colour code: Grey

Providing marked crosswalks is aimed at making it easier and safer for pedestrians to cross the road. However, there have been some conflicting studies and much controversy regarding the safety effects of marked crosswalks. The found literature remains inconclusive on the safety effects of marked crosswalks. The identified studies found no reduction in the number of crashes resulting from the installation of marked crosswalks. Two studies found no significant effect of marked crosswalks on the number of crashes. Another study found no significant effect of marked crosswalks on pedestrian crash rate for roads with relatively low traffic volumes, but a significant increase in pedestrian crash rate for high-volume roads with more than one lane in each direction was found. One study found an increase in the number of crashes between motor vehicles and older pedestrians. A number of studies looked into the severity of crashes at marked crosswalks and consistently found that the injury severity is significantly lower in crashes at crosswalks. Most results refer to crosswalks at intersections, only few refer to crashes at midblock crosswalks. Since the majority of studies took place in the United States, transferability of the results to the European context is somewhat uncertain. The heterogeneity in results, especially regarding the effect on crash rate, further limits the transferability of results. In conclusion, no evidence was found that marked crosswalks reduce the number of crashes, and some indications were found that an increase in the number of crashes might take place at some locations and for some categories of road users. Marked crosswalks do, however, reduce the severity of crashes.

Traffic signal installation

Colour code: Light Green

Traffic signal installation is a measure regarding the implementation of a pedestrian signal phase or improved traffic signal timing, and belong to the group of junction treatments. Six high quality studies, including two meta-analyses, were coded. Most studies show significant road safety benefits. Traffic signal installation was found to reduce total collisions by 29% in the first meta-analysis and the implementation of left-turn phase was found to reduce turning or crossing crashes by 15%. Overall, crash occurrence and severity are mitigated, although one specific crash type appears more frequent: rear-end crashes. On a basis of both study and effect numbers, it is evident that traffic signal installation measures have a mostly positive impact on road safety. Only rear-end crashes increased after the installation. The positive effects do outnumber the negative ones by a considerable margin, and many outcomes are statistically significant. The results seem generally transferable with caution.

Traffic signal reconfiguration

Colour code: Grey

Traffic signal reconfiguration is a measure regarding the implementation of a pedestrian signal phase or improved traffic signal timing, and belong to the group of junction treatments. Eight high quality studies, including two meta-analyses, were coded. On a basis of both study and effect numbers, it is evident that the effects of traffic signal reconfiguration measures on crash and conflict counts and on behavioural indicators are unclear or statistically not significant. The results of the two meta-analyses contribute to the unclear picture. The results seem generally not transferable overall, specific study results may be transferable with caution.

Appendix C Cost Benefit Analysis Abstracts

Road safety audits – Light measure case

Existing evaluation studies on the effects of road safety audits were analysed, and information was synthesized from several sources. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 21.7 when audits are used in tandem with a light engineering measure which means that the benefits highly exceed the costs (for a heavy measure example and the resulting change in BCR, see the Appendix C below). The BCR is sensitive to changes in the underlying assumptions as shown by the sensitivity analysis.

Road safety audits – Heavy measure case

The previous analyses is complemented by an additional scenario where the measure is in the heavy engineering category (instead of the light measure example of the previous analysis). The improvement of 1 km of rural road via either improving the cross section or general upgrading is used as an example; the cost of both measures is equal and is reported as 4,700,000 NOK/km in 2000 prices (Elvik et al., 2002). This is converted for inflation by applying the inflation conversion value of 1.63 and to Euros (EU-28 average) by dividing with the PPP conversion value of 12.87. Maintenance costs are assumed to be zero. This amounts to an extra implementation cost of 596,215Euros/km (Total implementation costs: 599,291 €/km).

The resulting best estimate of the benefit-to-cost ratio (BCR) is 2.9. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

High risk site treatment

Existing evaluation studies on the effects of high risk site treatment were analysed, and information was synthesized from several sources. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 16.1 which means that the benefits tend to highly exceed the costs. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

Dynamic Speed Limits

An existing evaluation study on effects of dynamic speed limits on motorways in Flanders, Belgium (De Pauw et al., 2017) was revisited. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 1.1 which means that the benefits tend to exceed the costs slightly. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

Section Control

A cost-benefit analysis on section control systems was executed based on effect estimates from the meta-analysis by Høye (2014), supplemented by cost estimates in Owen et al. (2016) and target crash estimates in Montella et al. (2012). The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio is 19.5 which means that the benefits clearly outweigh the costs. The sensitivity analyses show that this measure remains cost-effective in all scenarios, even in the worst case scenario.

Installation of speed humps

A meta-analysis regarding the effects of the installation of speed humps on accidents (Høye, 2015) was revisited. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-cost ratio (BCR) is 18.2 which means that the benefits tend to exceed the costs considerably. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis, however in all the scenarios it is shown that the installation of speed humps is a very cost-effective measure.

Implementation of 30 km/h zones

An existing cost-benefit and cost-utility analysis of mandatory 30km/h (20mph) zones in London (Peters & Anderson, 2013) was revisited. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 1.6 which means that the benefits tend to exceed the costs slightly. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

Area-wide traffic calming

A section of the road safety handbook (Elvik, Hoye, Vaa, & Sorensen, 2009) regarding the effects of the area-wide traffic calming on accidents, as well as a cost-benefit analysis of area-wide traffic calming in Greece (Yannis, Papadimitriou, & Evgenikos, 2005) were revisited. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 0.2-0.4 which means that the costs tend to exceed the benefits slightly. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis, however in all the scenarios it is shown that the implementation of area-wide traffic calming is slightly not cost-effective a measure.

Road Surface Treatment

An existing evaluation study on effects of road treatment (Hussein et al., 2016) was revisited. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The break-even costs indicate the maximal costs that one unit of a measure can have to still be economically efficient.

Winter maintenance

An existing evaluation study on effects of winter maintenance (Høye & Bjørnskau, 2013) was revisited. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. A benefit-to-cost ratio (BCR) > 1 indicates that a measure is economically efficient. The resulting best estimate of the BCR is 6.0 which means that the benefits tend to exceed the costs.

Road lighting

An exemplary cost-benefit analysis for the installation of road lighting was conducted using data from Høye (2014), Høye et al. (2017) and Perkins et al. (2015). The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 0.7 which means that the costs exceed the benefits. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

Implementation of rumble strips at centreline

An existing evaluation study on the effects of centreline rumble strips in USA (Lyon et al., 2015) was revisited. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 1.0 which means that the benefits tend to be equal to the costs. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

Automatic barriers

An existing meta-analysis on the effects of the installation of automatic barriers at rail-road crossing including international literature (Elvik, 2009) was revisited. For further analysis the SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 0.05 which means that the costs tend to exceed the effects. The BCR is not sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis (estimates are below one in all scenarios).

Safety barrier installation

Existing evaluation studies on the effects of safety barrier installation were analysed, and information was synthesized from several sources. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 19.5 which means that the benefits tend to highly exceed the costs. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

Installation of chevron signs

Existing evaluation studies on the effects installation of chevron signs were analysed, and information was synthesized from several sources. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 2.7 which means that the benefits tend to considerably exceed the costs. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

Channelisation

An existing meta-analysis on the effects of channelisation (installation of left turn lanes at crossroads) including international literature (Høye, 2013) was revisited. For further analysis the SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 8.4 which means that the effects tend to exceed the costs. The BCR is slightly sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

Roundabouts

An existing meta-analysis on the effects of the conversion of junctions to roundabouts (general effect) including international literature (Elvik, 2015) was revisited. For further analysis the SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. The resulting best estimate of the benefit-to-cost ratio (BCR) is 9.2 which means that the effects tend to exceed the costs. The BCR is not sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.

Traffic signal installation

Existing evaluation studies on the effects of traffic signal installation were analysed, and information was synthesized from several sources. The SafetyCube Economic Efficiency Evaluation (E3) Calculator was used. For county signals, the resulting best estimate of the benefit-to-cost ratio (BCR) is 1.1 which means that the benefits slightly exceed the costs. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis. An additional analysis for highways in provided in the Appendix C below.

Traffic signal installation on highways

The previous analysis is complemented by an additional scenario of traffic signal installation for highways; this amounts to different implementation and annual costs. The original Handbook (Elvik,

2009) mentions average implementation cost for traffic signal installation at 1,100,000 NOK and annual maintenance costs at 50,000 NOK per national highway junction. In both cases, they are converted for inflation by applying the inflation conversion value of 1.445 (they are 1995 prices) and to Euros (EU-28 average) by multiplying with the PPP conversion value of 0.078. For highway analysis, crash numbers per year were obtained from Agent and Green (2008) for 4-legged intersections of the USA.

The resulting best estimate of the benefit-to-cost ratio (BCR) is 3.7. The BCR is sensitive to changes in the underlying assumptions as it is shown by the sensitivity analysis.