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CEDR TRANSNATIONAL ROAD RESEARCH PROGRAMME

SAFEPATH

SAFE caPAciTy Highways

SAFEPATH: SAFE caPAciTy Highways

WP4000: Road Safety Analysis

Deliverable: D4.1, D4.2

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SAFEPATH: SAFE caPAciTy Highways

WP4000 Road safety analysis

D4.1 Initial Technical Report

D4.2 Final Safety Analysis Report

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Executive Summary

SAFEPATH

This final road safety analysis report is deliverable D4.2 from Work Package WP4000 of the SAFEPATH project.

Objective

The objective of the Road Safety Analysis Work Package (WP4000) is to investigate the safety impact of existing (e.g., hard shoulder) and evolving (e.g., Cooperative Intelligent Transport Systems (C-ITS)) highway capacity measures. The findings from WP4000 aim to provide a better understanding and insight into the impact on highway safety of any measure NRAs may wish to implement to increase capacity.

Approach

The road safety analysis report deliverable's scope is aligned with findings captured in WP2000 (Problem and System Analysis) and WP3000 (Empirical Research). For instance, the most relevant KPIs for road safety that are widely applicable within this project's scope are the collision risk and severity index, as highlighted in WP2000. Similarly, the safety impact investigation considers the set of capacity measures that were selected in WP3000.

In this study, two approaches to analyse the safety impact of capacity measures are used. The first approach focuses on finding evidence on each capacity measure’s safety impact using existing studies in the literature. In the second approach, system analysis is performed to create a model which can be used to estimate the potential safety impact of implementing a specific capacity measure. The safety impact estimation model focuses on the most important factors that are critical to understanding the system.

To collect evidence on each capacity solution’s safety impact and lessons learned from similar road capacity projects, we began with reports such as those from CEDR, ESTC, PIARC, and AASHTO, which already have published analysis findings and recommendations on highway safety. We also conducted a literature review on those scientific studies that emphasise pre-post analysis and surveys from NRAs.

Several measures, such as ITS and C-ITS services, are evolving, so their results are mostly derived from simulation data or controlled experiments instead of captured real world data. Therefore, the findings in this report contain evidence both from real-time analysis and simulation analysis. Providing evidence of both types is valuable to understanding capacity measures' safety performance level and, likely impacts of measures yet to be deployed at scale e.g., C-ITS.

Outcomes

The safety impacts of a set of selected capacity measures that align with WP3000 have been analysed. The selected measures and the determined safety performances are shown in the figure overleaf.

Category	Selected capacity measures	Safety performance
Infrastructure	Hard shoulder running	Probably effective
	High occupancy vehicle lane	Probably effective
	Mandatory variable speed limit	Effective
	Ramp metering	Unclear result
	Intelligent traffic control system	Probably effective
	Tidal flow operation	Unclear result
	Lane redesign and adjustments	Unclear result
	Traffic and route information	Probably effective
	Fog warning system	Probably effective
Road user behaviour	Speed enforcement using speed cameras	Effective
	Driver training and education	Probably effective
	Dynamic speed display signs	Effective
Vehicle technology	Intelligent speed adaptation	Probably effective
	HGV platooning	Unclear result
	Green light optimised speed advisory	Probably effective
Incident response	Faster response to incidents	Effective
	Access to emergency services	Effective
	Incident detection	Effective
	Institution cooperation	Effective
Regulations	Congestion pricing scheme	Probably effective
	Overtaking ban on HGVs	Effective

In addition, a safety impact analysis model has been developed which uncovers the building blocks affecting the system safety and underlying interactions. The model can be used to predict the impact of a capacity measure on overall safety. The model also provides a scientific understanding of various influencing risk factors, capacity measures, and criteria within the system of highway capacity and traffic safety.

NRAs can use the model to identify the most influential safety factors in their highway networks. This can help to further redefine their approach towards implementing a measure by considering its safety impact. A tool for estimating the safety impact level of capacity measures has also been developed, complementing this report. The tool is developed using Microsoft Excel software and can be used by running the file SAFEPATH-IIT.xlsx. SAFEPATH-IIT.xlsx also contains the capacity measures with an overview of their impact on highway safety, and other factors. Users can view and explore the capacity measures and safety factors, allowing them to get an indication on how different capacity measure influence safety factors.

Highlights from the road safety analysis are:

- There exists a wide variety of methods used to analyse safety for highways, in particular, *real-time data and predicated models such as regression methods, grey models, and time series methods.*

These methods need further research and coordination between practitioners to establish an agreed approach.

- Road Infrastructure Safety Management (RISM) provides a systematic approach to road safety. It sets out a "*common language*" for carrying out road infrastructure safety management.
- There is wide disparity in the *readiness of the measures in the SAFEPATH countries:* NRAs are already working on digitalisation and connectivity as enablers for improved services of the future. Within Europe, managed lanes are predominantly implemented in Western Europe and metropolitan areas. The way countries apply Traffic Incident Management (TIM) – in its organisation, responsibility, and specific measures – varies significantly across the region. Countries have different TIM priorities, dictated by geography, climate, and driver culture.
- We consider the *transferability of the measures*: Rather than directly applying the measures from any developed country, it is worth analysing the risk and cost of the measures that influence the development in new locations.

The report highlights some critical practical gaps:

- Many countries do not have accurate information on collisions. Until such data is available, information about road design features and key safety behaviours provides an important means of identifying high risk locations and ways to address them. For a long-term benefit and assessing the capacity measures performance, data collection is vital importance, at least for high-risk routes (e.g., high volume roads) to allow measurement of safety problems and identification of measures.
- RISM procedure is not fully implemented in most EU countries. The primary reason is the lack of resources or tools. However, certain countries have already initiated addressing the RISM gaps. For instance, road safety training courses have been activated in the Netherlands and Belgium to effectively address the lack of staff knowledge to carry out tasks. The UK and Ireland have developed clear and comprehensive guidelines for conducting road safety audits and inspections.
- The reasons behind deploying speed cameras, and with that also the set-up and use of camera systems, are different in different counties, making comparison difficult.
- Effective coordination and cooperation between emergency services restores capacity more rapidly. However, there are critical gaps and challenges encountered in this area. The main problems related to information sharing, communication, and coordination have been identified as the bottlenecks for effective cooperation between emergency services. However, organisations are starting to realise that introducing new interoperable system concepts forms an important basis for significantly improving cooperation. One of the interoperable solutions is to support information-sharing between public and private emergency services and road authorities.

The findings of this report support the Practitioners Guide (WP5000). The Guide will enable NRAs to make informed decisions when selecting measures to increase capacity.

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List of Acronyms

ACC	Adaptive Cruise Control
ACN	Automatic Crash Notification
ADAS	Advanced Driver-Assistance Systems
AEB	Automated Emergency Braking
ALR	All Lane Running (motorways)
AMCIS	Advance Motorway Condition Information Signs
ASEC	Average Speed Enforcement Cameras
CEDR	Conference of European Directors of Roads
C-ITS	Cooperative Intelligent Transport Systems
DoRN	Description of Research Needs (CEDR call for proposal 2019(2))
DMS	Dynamic Message Signs
DSDS	Dynamic Speed Display Signs
EAT	Efficiency Assessment Tools
EU	European Union
FPLT	Formal Pre-license Training
GDL	Graduated Driver Licensing
GLOSA	Green Light Optimised Speed Advisory
HGV	Heavy Goods Vehicles
HRS	High-Risk Sites
ISA	Intelligent Speed Adaptation
iRAP	International Road Assessment Programme
iVRI	Intelligent Traffic Control Systems
	(Translated from Dutch - Intelligente verkeersregelinstallaties)
ITS	Intelligent Transport Systems
KSI	Killed or Seriously Injured
KPI	Key Performance Indicator
LDW	Lane Departure Warning
LKA	Lane Keeping Assistants
MAIS	Maximum Abbreviated Injury Scale

MCIS	Motorway Condition Information Signs
NRA	National Road Authority
NSR	Network Safety Ranking
RAP	Road Assessment Program
RIA	Road Safety Impact Assessments
RISM	Road Infrastructure Safety Management (RISM)
RSA	Road Safety Audits
RSI	Road Safety Inspections
SPI	Safety Performance Indicators
SWOV	Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (national scientific institute for road safety research in the Netherlands)
TIM	Traffic Incident Management
VMS	Variable Message Signs
VSL	Variable Speed Limits

Key Terms

The following terms are used frequently in road safety analysis in different steps. The definitions of these terms are given below.

System: *A* System is defined as a part of reality which is being studied and whose boundaries are defined by the problem *statement*. For example, in this project, system refers to the collection and relation between various means, influencing factors, external factors, KPIs and objectives referring to increasing road capacity and highway safety.

Objectives: Objectives refer to the *desired situation relevant to the project*. The main objective in this project defined within Description of Research Needs (DoRN) is to increase highway capacity without compromising with traffic safety and without physically widening the highway.

Means: Means are the *instruments or measures* through which a system can be affected and through which objectives are achieved. For example, increasing the number of lanes is a means to increase highway capacity.

External factors: External factors are the *elements which cannot be influenced* by any means or factors inside the system but play an important role in the outcome. For example, Weather cannot be influenced by any means and thus is an external factor.

Criteria: Criteria are the *key performance indicators* (KPIs) which can quantify and measure the achievement of objectives. For example, traffic flow can be measured to estimate the highway capacity.

SAFEPATH countries: The participating countries in the call 2019(2) under CEDR Transnational Road Research Programme are Austria, Belgium (Wallonia), Finland, Germany, Hungary, Ireland, the Netherlands, Sweden, and the United Kingdom.

1 Introduction

Traffic safety is a public health concern that affects all road users and stakeholders. This calls for a concerted response especially with respect to the safety of a highway system, as indicated by the frequency and severity of collisions. Traffic incidents not only cause danger to and loss of life, but they also cause congestion and generate economic costs. Though the EU road safety target in 2020 was not met, all EU countries made improvements in terms of reduced road deaths.

The report "*EU Ranking on Road Safety"* published by ETSC [1] in 2021 charts the change in the number of road deaths and severe injuries in the EU. It shows that the largest annual reduction in the number of road deaths in the EU – 3,919 or a 17% reduction – was achieved in 2020. This 17% decrease in just one year, however, was an exceptional result, due to the reduction in general travel resulting from Covid 19 precautions. The progress in reducing serious road traffic injuries in the last decade has been poor in comparison with the reduction in deaths.

With the continuously growing demand on highways, safety is one of the primary determinants that, if not reinforced adequately, can cause adverse implications on traffic flow and hence capacity. Alongside driver behaviour and vehicles, infrastructure is widely acknowledged to be the third element of any comprehensive road safety programme. Its contribution to improved safety is pivotal: well-designed roads can help minimise the risk that a collision will occur [1].

There are already technologies in place that aid in mitigating safety problems and maintaining smooth traffic flow on highways. While some are already implemented, such as shoulder treatments and centre medians, new advancements are gradually being implemented, such as managed lanes.

The question is how well do capacity solutions impact safety on highways? Accurate safety performance data is crucial for National Road Authorities (NRAs) to help them make better safety decisions in improving highway capacity. Currently, there is a lack of such evidence for capacity measures. As a result, there is a risk of an NRA choosing a deployment solution that may worsen the safety on roads. The objective of WP4000 is to fill those gaps by investigating existing and evolving capacity measures' safety impact and performance.

The findings from WP4000 will facilitate NRAs to gain a better understanding and insights into the capacity solutions' impact on safety on highways. This is done by analysing the safety performance of highway capacity measures.

1.1 Scope

The work in WP4000 was carried out in two phases. This is the final report of WP4000 (after phase 2) and is an update over the previous deliverable D4.1.

Within this project, the focus was on collecting, consolidating, coordinating, and analysing information from existing research within the defined scope. The solutions and measures thus identified have been reviewed to quantify their impact on safety. The analysis in this report mainly includes pre-post investigation studies published either in reports such as CEDR, ETSC, or scientific studies. The commentary in this report is based on the evidence captured from literature studies. The measures considered are applicable for the Major Highways (Motorways) within the Trans-European Road Network (TEN-T). City streets and connecting highways are out of the scope of this report.

Findings on the capacity aspects of the various measures is out of the scope of this work package and has been covered in Empirical Research (WP3000).

Table 1 shows the Description of Research Needs (DoRN) requirements relevant to WP4000 and provides an overview of where different aspects are covered. Other requirements which are not mentioned are covered in work packages: Problem and system analysis (WP2000), empirical research (WP3000), Practitioners Guide (WP5000) and final report (WP6000).

Table 1: Requirement assessment from DoRN

Requirement(s) from DoRN (page 4)	Covered under
Commentary on the safety performance of various solutions that increase highway capacity	**D4.2 (This report)** Section 6 contains comments on the safety performance of various solutions that increase highway capacity.
Commentary about the impact on road safety of measures that increase the capacity of highway due to future developments	**D4.2 (This report)** Section 8.2 and SAFEPATH-IIT.xlsx file contains comments and findings on road safety implications of measures that increase the capacity of highway due to future developments. Section 9 describes the readiness of the measures in SAFEPATH countries.
Likely changes of the primary collision types before and after the implementation of the highway capacity improvement scheme	**D4.2 (This report)** Section 4.4 contains comments on likely changes of the primary collision types before and after the implementation of the highway capacity measures.
A methodology of defining road safety during normal operation	**D4.2 (This report)** Section 3 gives the methodology used in this report, Section 5 provides methodologies for defining road safety during normal operation (pre- and post-measure being implemented), Section 7 presents the developed system analysis model for safety impact analysis.
Commentary on the transferability of different options to the EU Member States	**D4.2 (This report)** Section 9.4 comments on transferability of different measures.
A detailed list of references and sources of information to allow Roads Authorities to facilitate further research.	**D4.2 (This report)** Section 12 contains references and sources of information.

Note that most NRA's build, operate and manage strategic roads, rather than city roads. But some also manage strategic roads that are not motorways or freeways, e.g., are open to all traffic and have maybe just two lanes. They use "city tools" like traffic signals to manage these roads. Traffic signals are also used to manage entry and exit to the NRA network so have been included in this report where appropriate as they are a useful tool.

1.2 Outline

The report structure is as follows:

- **Section 2** discusses the various alternative approaches considered for analysing safety impact of a capacity measure.
- **Section 3** gives the methodology used in WP4000.
- **Section 4** focuses on safety indicators, safety factors and KPIs that are critical on highway capacity**.**
- **Section 5** presents the methods used to assess the real-time analysis and prediction of the collisions.
- **Section 6** describes the safety performance of the capacity measures identified in WP3000.
- **Section 7** presents the road safety system model we developed.
- **Section 8** provides an overview of the SAFEPATH impact indicator tool and presents information on usage of it.
- **Section 9** describes the readiness of the measures in SAFEPATH countries.
- **Section 10** focuses on speed management.
- **Section 11** concludes the report and explains next steps.
- Section **12** contains references and sources of information.

2 Approaches for safety impact analysis of capacity measures

Safety impact analysis is the process of developing estimates of how a capacity measure has impacted collision frequencies or severities. Analysis of safety impact leads to an assessment of how collision frequency or severity has changed due to a specific capacity measure. The analysis gives an output on whether the capacity measure has a positive or negative impact on safety.

This section discusses the various alternative approaches considered and highlights which model is appropriate for assessing safety impact in the scope of this study.

Three approaches can be used for the analysis of the safety impact of capacity measures:

1. Pre-post analysis for the safety impact of capacity measures,
2. Evidence-based safety impact analysis of capacity measures,
3. System analysis model to estimate safety impact of capacity measures.

2.1 Pre-post analysis for the safety impact of capacity measures

Pre-post analysis studies compare the count of collisions and their severity at a site before application of the capacity measure to the count of collisions at a site after its application to estimate the benefits of a measure. This method relies on the assumption that site conditions such as weather, surrounding land use and driver demographics have remained constant.

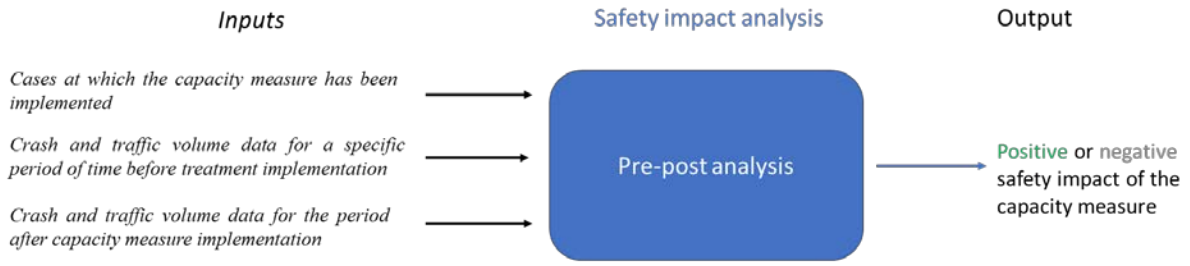


Figure 1. Pre-post analysis model for the safety impact of capacity measures

Figure 1 shows the steps in the process of pre-post analysis. The data needed as input to a pre-post analysis evaluation include:

1. Cases where the capacity measure has been implemented
2. Collision and traffic volume data for a specific period before implementation
3. Collision and traffic volume data for the period after capacity measure implementation

The safety impact of the capacity measure is evaluated using the percentage change in collisions and severity. Both descriptive and predicted analysis methods can be used to perform the safety impact analysis. Descriptive analyses focus on summarising and quantifying information about collisions that have occurred at a site. Predictive analyses focus on estimating the expected average number and severity of collisions at sites with similar geometric and operational characteristics.

A safety impact analysis study can be performed with fewer cases and/or shorter time periods, but statistically significant results are less likely. The output of the pre-post analysis will give whether the capacity measure will have a positive or negative safety impact.

2.2 Evidence-based safety impact analysis of capacity measures

In evidence-based safety impact analysis of capacity measures, the data is collected from the existing studies and the information in those studies on safety impacts of the capacity measures is used to determine the safety impact levels of the capacity measures. There are three blocks of the evidence-based safety impact analysis of capacity measures model: Data collection, Safety analysis, and Output.

Figure 2. Model for evidence-based safety impact analysis of capacity measures

Figure 2 shows the model of the evidence-based safety impact analysis. The blocks of the model include:

Data collection: The literature and safety reports are investigated. A mapping study is performed on those scientific studies that focus on pre-post analysis and survey-based information. Representing the evidence of real-time data analysis and simulation enables a clear understanding of the measure's safety impact.

Safety impact analysis: This analysis is done on the capacity measures to assess their performance in mitigating collisions and their severity. The capacity measures' safety impact is analysed using the safety related information captured from data collection phase.

Output: Safety impact level of the capacity measures is provided. The generalised information provides evidence on the outlook of the safety performance of a particular measure.

2.3 System analysis model to estimate safety impact of capacity measures

The structure for safety impact analysis can be modelled using the systems analysis approach. The system analysis model facilitates making conclusions on how different means affect different criteria. This is done with the help of causal chains. Furthermore, the factors which need to be influenced to achieve an objective can be determined with the help of systems diagram.

There are four main elements in the systems diagram (Figure 3).

Capacity measures (shown on the left side) are the actions which can influence the system to achieve objectives.

Criteria (shown on the right side) are the factors whose values indicate the degree of influence and quantified the achievement of objective.

External factors (presented at the top) are the factors which cannot be influenced by any means.

Internal factors (presented in the centre) are the factors affected by means and which affect the criteria.

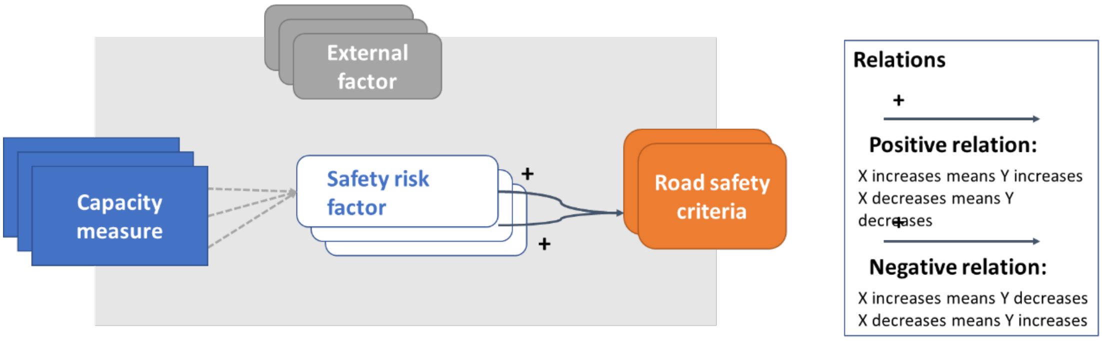


Figure 3. System analysis model to estimate safety impact of capacity measures

Using the model shown in Figure 3 can establish whether the safety impact of a capacity measure will be a positive or negative impact can be estimated.

2.4 Our approach

To perform a pre-post analysis for the safety impact of capacity measures, a quantitative model which uses the data before and after the capacity measure implemented is needed. Due to limitations in the data available, pre-post analysis is not a feasible option for this study.

We will therefore use the approach described in Section 2.2, which focuses on finding evidence on each capacity measure's safety impact using existing studies in the literature, as the safety assessment methodology of WP4000. We will then develop a system analysis model for safety analysis as introduced in Section 2.3 that can be used to estimate the potential safety impact of implementing a specific capacity measure.

Section 6 provides the output of evidence-based analysis, and Section 7 describes the model that we developed which provides a scientific understanding of various influencing factors, capacity measures, and criteria within the system of highway capacity and traffic safety.

3 Methodology

The methodology used to investigate the current state of knowledge on highways safety is shown in Figure 4. It consists of three parts which are explained in detail in the following sections.

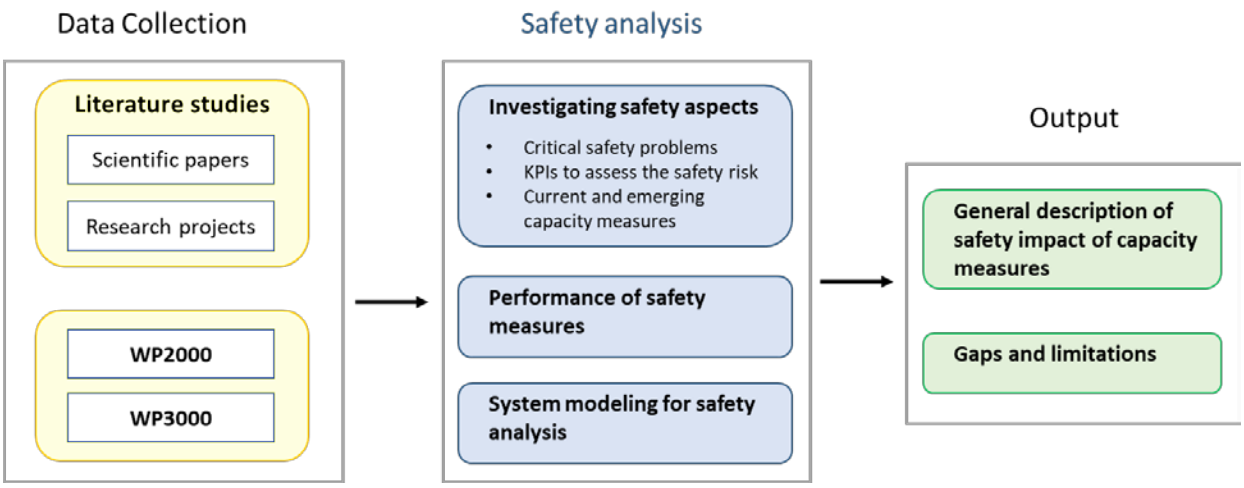


Figure 4: WP4000 methodology

3.1 Data collection

One of the tasks for WP4000 was to build the safety methodology on the research carried out in similar road safety projects. We focused on capturing the current state of knowledge from both scientific research and practical projects. We investigated reports such as CEDR, ESTC, and AASHTO. We performed a review on those scientific studies that focus on pre-post analysis and any NRAs survey-based information. The pre-post analysis results are either derived from real data analysis or simulated data in the case of ITS and C-ITS evolving technologies.

Many C-ITS solutions are still under development or at the experimental stage, so the data in these cases are all from simulation-based results.

Using the evidence of real data analysis and simulation enables a clear understanding of the measure's readiness. We used findings from WP2000 and WP3000 on safety KPIs and highway capacity respectively. We also collected data using stakeholder engagement. NRAs' input is crucial to verify the credibility of the captured evidence.

3.2 Safety analysis

Safety analysis of the capacity measures assesses their performance in reducing the number and severity of collisions. The identification of highway capacity measures was carried out under WP3000. We analysed the safety performance of the selected measures which have the most comprehensive evidence of impact on capacity.

We prioritised measures which lie within NRA's power – for example, NRAs influence infrastructure (road design and roadside) solutions rather than in-vehicle ones. For instance, in this study a collision caused by drug or alcohol consumption is less relevant than a collision caused by poor road design, because the NRA has more influence over the latter.

We analysed the selected measures' benefits, limitations, and knowledge gaps captured from the existing studies and literature review. We mainly focus on pre-post analysis studies and surveys results or reports from NRAs. We describe the relationship of the critical factors that cause collisions. For example, poor road design causes severe injuries in collision. Furthermore, we analysed the KPIs and described the general methodologies used to evaluate them (e.g., real data models and prediction models).

We also developed a system model for estimating the safety impact of capacity measures. The model predicts whether the safety impact of a capacity measure will be positive or negative. The model also provides a scientific understanding of various influencing risk factors, capacity measures, and criteria within the system of highway capacity and traffic safety.

3.3 Output

To align with the expectation from the DoRN document of providing “commentary” on safety aspects, we summarised general benefits, gaps, and limitations of the safety impact of the selective capacity measures. The information is derived from the current and ongoing activities carried out in Europe. This generalised information provides enough evidence on the safety performance of each measure.

We carried out a separate analysis of the current state of these measures within individual SAFEPATH countries, to assess the readiness of these measures in each country.

4 Safety indicators and safety factors

4.1 Highway safety

Incidents are a significant cause of congestion and can cause a decrease in highway capacity. Among numerous indicators, the most relevant criteria for road safety applicable within the scope of this project are minimum collision risk and minimum collision severity, as identified in WP2000.

- *Minimum collision risk:* Collision risk (or previously accident risk) is defined as the probability of encountering a collision while driving. Collision risk is measured in various units. The *number of collisions per billion vehicle kilometres travelled* is chosen as an appropriate unit for this project.
- *Minimum collision severity:* Based on the roadside collision data, the severity is assessed by occupant injuries. In the EU, the Maximum Abbreviated Injury Scale (MAIS) is used to classify the seriousness of injuries. Injury scores range from 1 to 6, where 6 represents maximum injury (fatality), 3+ indicates serious injury, 1+ indicates minor injury, and 1 indicates minimum injury (material damage only).

Although strategic highways run by the NRAs exhibit reduced collision rates compared to other road types, collisions still occur. According to Motorways 2018 [40], there are three types of collisions on highways that are critical and result in fatalities or severe injuries:

- *Roadside hazards (single vehicle run-off-road collisions)* – When vehicle speed is high, collisions that involve running into roadside hazards tend to be more severe. In 80 km/h speed limits, 1 in 25 recorded run-off-road casualty collisions will be fatal. In 110 km/h speed limits, 1 in 15 will result in a fatality.
- *Collision caused by the improper use of emergency lanes – People* who use emergency lanes to cut ahead in traffic will often break multiple laws in a short period of time and can cause collisions.
- *Head-on cross-median collisions* – collisions that are typically the result of improper driver actions, commonly in combination with other adverse circumstances, such as weather conditions or motorist fatigue.

To diagnose and understand the process that leads to collisions, various safety performance indicators are used that monitor the performance of different parts of the road traffic system. Safety performance indicators may include behavioural measures such as average vehicle speed and vehicle safety ratings, infrastructure measures, including road safety ratings, % of high-volume and high-speed roads divided by a median, and post-crash care indicators such as emergency vehicle response times. Our next section describes the performance indicators critical for collisions on highways.

4.2 Highway safety performance indicators

Performance indicators are directly related to collisions or injuries, and they serve as diagnostic tools for understanding the processes leading to road collisions, to help experts and policymakers understand how they can contribute to improved road safety [2]. We provide a comprehensive list of KPIs used to assess the collision risk based on the severity levels (e.g., fatal injuries) and the causes, such as speeding, in Table 2.

Table 2: Performance indicators for assessing safety on highways

Safety Performance Indicators	Equation	Formula	Category
Mortality index	(Number of Deaths / Number of Collisions) *100	D/A	Collision
Severity index	(Number of Injuries / Number of Collisions) *100	I/A	Collision
Severity rates	(Number of Injuries / Area Population) *1000	I/P	Collision
Hazard ratio	(Number of Deaths / (Number of Deaths + Number of Injuries))*100	D/(D+I)	Collision
Flow ratio	Damaged vehicles / Vehicles in circulation	[-]	Collision
Accident / Collision rate	Number of Accidents (Collisions) / kilometre	A/km	Collision
Fatalities from psychoactive substances	Percentage of fatal collisions, where at least one road user is under psychoactive drugs (not easily realisable)	N/A	Collision
Fatalities from alcohol	Percentage of fatal collisions, where at least one road user is under alcohol	N/A	Collision
Fatalities from drugs	Percentage of fatal collisions, where at least one road user is under drugs **other than alcohol**	N/A	Collision
Average speed	Average speed in free flow conditions (no traffic)	Σspeed/number of vehicles	speed
Speed STD	Standard deviation of average speed	STD(speed(sample), average speed)	speed
85th percentile of unconstrained speed	85th percentile of unconstrained speed for the vehicle data set	85(n+1)/100	speed
percentage of vehicles over the speed limit	fraction of the vehicles over the speed limit w.r.t. the total number of vehicles	(vehicles(speed>legal speed)/total vehicles) *100	speed

Apart from the KPIs mentioned in the above table, the high-level indicators attributed to the road system's performance are part of the EU Vision Zero safe system strategy [41]. A recent report, "Developing safe system road safety indicators for the UK," recommended eight indicators and the approach to support them [3]:

1. Traffic complying with speed limits on national roads
2. Traffic complying with speed limits on local roads
3. Drivers who do not drive after consuming alcohol or drugs
4. Car occupants using a seat belt or child seat
5. Drivers not using an in-car phone

6. Passenger cars with highest safety rating
7. Major roads with appropriate safety ratings
8. Emergency medical services arriving at priority accident scenes within 18 minutes.

The consolidated version of these indicators relevant to NRA roads and policies are:

- **Indicator 1:** Percentage of traffic complying with speed limits on national roads (by road type, speed limit, and vehicle type)
- **Indicator 2:** Percentage of new passenger cars with the highest Euro NCAP safety rating
- **Indicator 3:** Percentage of roads with appropriate iRAP safety ratings
- **Indicator 4:** Percentage of emergency medical services arriving at the collision scene within 18 minutes of notification

Gap:

PIARC, in their road safety manual, A Guide for Practitioners, 2019 identified that many countries do not have accurate information on collisions. Until such data are available, information about road design features and key safety behaviours provides an important means of identifying high risk locations and ways to address them. However, for a long-term benefit and assessing the capacity measures performance, data collection is vital, at least for high-risk routes (e.g., high volume roads) to allow measurement of safety problems and identification of measures. There are a number of consequences associated with poor data quality and under-reporting of crash data [39]. Some include:

- Misleading information may cause road authorities to make probably ineffective and faulty road safety decisions and set inappropriate priorities;
- The success rates of implemented countermeasures cannot be fully assessed;
- Comparisons between jurisdictions and countries cannot be accurately made.

4.3 Highway safety factors

By investigating the causative mechanism of roadside collisions, some studies have explored the risk factors that affect the frequency and severity of roadside collisions. Such analysis helped implement corrective measures to improve roadside safety and reduce roadside collision losses, such as driver management, vehicle review, and road optimisation design [1]. These factors are critical as they influence the number of collisions, which affects the highway capacity.

Based on the analysis of highway roadside safety by Guozhu Cheng in 2021 [2], the European road safety decision support system (SafetycubeDSS)[1] and WP2000 Deliverable 2.3 [59], we identify the safety factors that affect highway capacity (Table 3). Factors such as alcohol or drugs and few parking spots for HGV are not included as they do not show a direct influence on the capacity increase.

The safety risk factors contributing to collision frequency and severity are listed in Table 3. For some of the factors there are (minimum) requirements in the regulations e.g., for the horizontal alignment deficiencies. Listed risk factors are the ones which have some evidence in the literature that exposure to the risk factor increases collision risk or collision severity.

[1] A tool available on https://www.roadsafety-dss.eu/#/

Table 3: Critical safety factors attributing to collisions frequency and collision severity

Critical safety factors	Specific risk factor	Collision Impact
Road surface deficiencies	*Inadequate skid resistance, uneven surface (rutting and longitudinal evenness), ice, snow etc.*	*High collision rate*
Cross-section deficiencies	*Number of lanes*	*High collision rate*
Workzone length	*Presence of workzone, workzone length, workzone duration*	*Increase the probability of collision occurrence*
Horizontal alignment deficiencies	*Low curve radius*	*The smaller the curve radius, the larger the risk for fatal single vehicle collisions*
Shoulder and roadside deficiencies	*Absence of paved shoulders, Narrow shoulders, Objects such as poles and trees adjacent to the lane*	*Increases the risk of run-of-road collisions, Increase the probability of collision occurrence*
Average driving speed	Average driving speed of different road users in a particular road segment	*Higher the driven speed, the more likely it is for a collision to occur. Driving speed has a direct influence on severity of collision*
Emergency services	*Inadequate post-crash services*	*High fatalities rate upon not immediate reaction*
Braking distance	*Misjudgement of braking distance which is dependent on multiple factors including speed and coefficient of friction*	*Probability of getting into a collision increases*
Traffic flow	*Traffic volume, congestion, varying traffic composition, temporary lane drop*	*High traffic flow can lead to high collision risk*
Adherence to traffic rules	*Driving up to the speed limit, prohibiting use of mobile phone while driving, prohibiting driving under influence of alcohol and drugs, respecting traffic signals and signs, maintaining safe headway from other vehicles*	*Adherence to traffic rules, road users are expected to drive and behave in a safe manner leading to a decrease in collision risk*
Speed differences	*Homogeneity of speeds in traffic, standard deviation of speed differences between different road users*	*higher collision risk and more severe collisions when there are high speed differences*

Lane changes	*Frequency of lane changes by all road users*	*Higher occurrence of lane changes, increases the collision risk*
Mass of vehicle(s)	*The mass of vehicle(s) getting involved in a collision*	*Upon collision, due to large mass, more energy is released leading to higher damage and severity of collision*
Poor Visibility – Darkness (cars only)	*Lighting increase visibility*	*Poor visibility – darkness- increases collision risk for cars*
Heavy goods vehicles – risks resulting from the blind spot issue	*Blind spot issue by right turning truck*	*Higher collision risk resulting from the blind spot issue by right turning truck*
Passenger car – injury mechanism – risk of injury	*Passenger car injury mechanism*	*Upon rollover of passenger cars, due to bad injury mechanism, higher damage, and severity of collision*

4.4 Primary collision types

Collision types are briefly highlighted in section 3.1. We elaborate more in this section. Primary collision types on highways, taken from a report by the Virginia Department of Transportation [54], are summarised in Table 4.

Table 4: Collision types

Collision type	Description
Rear End	A collision in which the front-end of one vehicle collides with the rear end of another vehicle.
Angle	A collision in which the front-end of one vehicle collides with the side of another vehicle. An angle collision occurs when vehicles collide while traveling on crossing paths.
Head on	A collision in which the front-end of one vehicle collides with the front-end of another vehicle.
Sideswipe – Same direction of travel	A collision in which the side of a vehicle collides with the side of another vehicle traveling in the same direction.
Sideswipe – Opposite direction of travel	A collision in which the side of a vehicle collides with the side of another vehicle traveling in the opposite direction.
Fixed object in road (from ditch to ditch)	A collision in which a vehicle collides with a fixed object in the roadway. “In the Roadway” is defined as from ditch to ditch.
Train	A collision in which a motor vehicle collides with a locomotive, rail car, light rail train, or other type of train.
Non-Collision, overturned, jack-knifed, or ran off road (no object)	A collision event not involving a collision. Includes overturn/rollover, fire/explosion, immersion, jack-knife, cargo/equipment loss or shift, equipment failure, separation of units, ran off road, cross median, cross

	centreline, downhill runaway, fell/jumped from motor vehicle, and thrown or falling objects.
Fixed object off road (from outside of ditch)	A collision in which a vehicle collides with a fixed object outside of the roadway. “Outside of the roadway” is defined as outside of the ditch line.
Animal	A collision in which a vehicle collides with an animal.
Pedestrian	A collision in which a vehicle collides with a pedestrian.
Backed into	A collision in which a vehicle in reverse collides with another vehicle or object.

The above data types from the US exclude cycles which should only be found on some specific NRA roads.

Different highway safety factors and combinations of them may affect different collision types. For instance, speeding may be associated with single-vehicle ran-off road collisions, whereas junction design or road design may be more strongly associated with collisions involving two vehicles [53].

Each safety factor contributing to a specific collision type and its possible outcomes must be assessed and addressed by one or more specific measure. Consequently, all measures can be classified as primarily addressing different components of the accident chain [53]:

- *Measures addressing collision types*: there are several measures that aim to prevent specific types, regardless of the risk factor(s) involved. Examples include ADAS and in-vehicle systems for longitudinal and lateral cruise control. Lane Departure Warning systems warn in cases of running off-lane, regardless of whether this is caused by distraction, fatigue, alcohol, speed, inappropriate curve design or any other factor.
- *Measures addressing injury severity*: again, regardless of the risk factor that causes the collision, there are measures directly aiming at mitigating the consequences of the collision. These include passive safety systems, protective systems (seat belts, helmets, and clothing) both via legislation and enforcement, dealing with road visibility and obstacles.

Typical factors which may add to several risks, such as head-on collision risk, or rear-end collision risk are listed in the International Road Assessment Programme (iRAP) Road Safety Toolkit [70]. Circumstantial risks and the type of collision they impact [53] are shown in *Table 5*.

Table 5: Circumstantial risks and crash types

Circumstantial risks	Collision types
Road surface deficiencies	Single vehicle accident, run-off road, Rear end collisions (same direction traffic)
Poor visibility and lighting	Pedestrian accident, Bicycle accident, Rear end collisions (same direction traffic), Junction accident
Technical defects / Maintenance of the road or the vehicle itself	All

Speed choice	All
Influenced driving (alcohol/drugs)	All

5 Methodologies to define road safety during normal operation

5.1 Safety analysis methods

We investigated existing methods of highway safety analysis. Table 6 summarises the identified methods for different categories as well as the scope of these methods. These methods need further research and coordination between practitioners to establish an agreed approach.

Table 6. Safety analysis methods for highways

Category	Method	Domain of interest	Scope
Deterministic - scenario analysis [73]	Raw data comparison	Highway capacity and safety	Present, compare raw data from national or international agencies and derive conclusions
Regression methods [72]	Negative binomial	Highway capacity and safety	Predict the future of the objective variable based on past values
	Linear regression	Highway capacity and safety	Predict the future of the objective variable based on past values
	Poisson regression	Highway capacity and safety	Predict the future of the objective variable based on past values
Time series method [72]	Exponential smoothing	Highway capacity and safety	Predict the future of the objective variable based on past values
	Auto Regressive Moving Average (ARMA)	Highway capacity and safety	Predict the future of the objective variable based on past values
	Auto Regressive Integrated Moving Average (ARIMA)	Highway capacity and safety	Predict the future of the objective variable based on past values
	Functional Auto Regressive (FAR)	Highway capacity and safety	Predict the future of the objective variable based on past values
Markov Models [72]	Markov Chain Model	Highway capacity and safety	Predict the future of the objective variable based on past values
Grey models [72]	Grey model	Highway capacity and safety	Predict the future of the objective variable based on past values (not requiring a big amount of data)
Stochastic / probabilistic networks [74]	Stochastic mathematical networks	Highway capacity	Usage of stochastic methodologies to estimate and investigate highway capacity
Bayesian networks [75]	Empirical Bayes (EB)	Highway capacity and safety	Methodology to predict the output from existing data
	Full Bayesian	Highway capacity and safety	Methodology to predict the output from existing data, more robust from EB
Decision making methods [76]	Analytical Hierarchy Process	Highway capacity and safety	Score the importance of factors
	Analytical Network Process	Highway capacity and safety	Score the importance of factors

5.2 How NRAs assess and cater for road user safety specific measures

As indicated in the DoRN document, routine works and cyclical programmes such as road safety inspections are one of the road user safety specific measures, so Road Infrastructure Safety Management (RISM) can be used to assess road user safety concerns. RISM refers to a set of procedures that support NRAs in decision making related to the improvement of safety on a road network, and, as result, maintain appropriate highway capacity.

The Highway Safety Manual [37] refers to roadway safety management as a “quantitative, systematic process for studying roadway collisions and characteristics of the roadway system and those who use the system, which includes identifying potential improvements, implementing, and evaluating the improvements” (AASHTO, 2010).

Road infrastructure safety management is legally specified in Directive 2008/96/EC of the European Parliament. The Directive introduces the use of Road Safety Audits (RSAs), Road Safety Impact Assessments (RIAs), Network Safety Ranking (NSR), High-Risk Sites (HRS), and Road Safety Inspections (RSIs). These procedures and others are proven to be effective in preventing collisions in some (developed) countries and have the potential to be just as effective in other countries.

An ex-post assessment in the form of an online questionnaire-based survey was carried out to collect evidence from NRAs, national authorities, and a broad range of stakeholders in 2016 [1]. The survey results highlighted RISM as a more systematic approach to road safety. The Directive has triggered a different way of thinking and dealing with road safety management, and it sets out a “common language” for carrying out road infrastructure safety management.

RISM benefits were published in the latest DIRECTIVE (EU) 2019/1936 of the European Parliament. The road infrastructure safety management procedures implemented on the TEN-T network have helped reduce fatalities and severe injuries in the European Union. It is clear from the evaluation of the effects of Directive 2008/96/EC that applying RISM principles voluntarily to their national roads beyond the TEN-T network has achieved much better road safety performance than in other Member States who have not. Therefore, it is desirable for those RISM principles to be applied to other parts of the European road network.

Gaps:

The RISM procedure is not fully implemented in most EU countries. Based on the survey done by IRTAD among 23 countries [9], RSI, RSA and HRS seem to be fully implemented in just half of the investigated countries, while In-depth collision investigation and safety performance indicators (SPI) are "fully" implemented in only a few countries. The main reason for not applying a RISM procedure is the lack of resources or tools. Another frequent reason is the absence of recommendations or legislation, especially for: SPIs, RAPs, RSIs and RSA. This highlights the importance of legislation regulating the application of the procedures. A lack of data has been found important mainly for SPIs, HRSs and EATs. Lack of know-how is a frequent issue found for RIAs and RSAs.

However, certain countries have already initiated addressing the RISM gaps. For instance, road safety training courses have been implemented in the Netherlands, Belgium, and the USA to address the lack of staff knowledge to carry out tasks. The UK and Ireland have developed clear and comprehensive guidelines for conducting road safety audits and inspections. Important international initiatives for providing standardized and accurate methods or tools for estimating the safety effects of road safety measures are The Handbook of Road Safety Measures [36] and the Highway Safety Manual by AASHTO [38].

6 Safety performance of capacity measures

The identification of highway capacity measures was carried out under WP3000. This included analysis to select the measures which have the most comprehensive evidence of impact on capacity. The measure categories and the "selected capacity measures", on the basis of stronger supporting evidence, are shown in Table 7.

In this section, these measures are analysed further to assess their safety performance. The analysis focuses on finding evidence of each capacity measure's safety impact using existing studies in the literature.

The sections below provide a summary of this analysis.

Table 7: Capacity measure categories and the selected measures

Category	Selected capacity measures
Infrastructure	Hard shoulder running High occupancy vehicle lane Mandatory variable speed limit Ramp metering Intelligent traffic control system Tidal flow operation Lane redesign and adjustments Traffic and route information Fog warning system
Road user behaviour	Speed enforcement using speed cameras Driver training and education Dynamic speed display signs
Vehicle technology	Intelligent speed adaptation HGV platooning Green light optimised speed advisory
Incident response	Faster response to incidents Access to emergency services Incident detection Institution cooperation
Regulations	Congestion pricing scheme Overtaking ban on HGVs

The safety performance of the selected capacity measures is classified into *Effective, Probably Effective and Unclear* rankings, influenced by the *SafetyCubeDSS*[2] project, funded by the EU commission.

SafetyCubeDSS is the first global system to combine knowledge of road safety risks and measures. It brings together European and international evidence on what causes collisions and injuries on our roads – and what interventions have shown to effectively mitigate these threats. We used their

[2] https://www.roadsafety-dss.eu/#/

approach while determining the rankings for the safety performance of capacity measures. An "Effective" ranking means consistent results showing a decreased risk. A "Probably effective" ranking corresponds to some evidence that there is a reduced risk, but results are not consistent. "Unclear" ranking corresponds to no conclusion being possible because of few studies with weak indicators.

6.1 SAFEPATH infrastructure measures

Nine infrastructure capacity measures with strong evidence base were identified in earlier SAFEPATH research. An analysis of their impact on road safety is given below.

6.1.1 SAFEPATH selected measure: Hard shoulder running

Safety performance	Significance	Sources
Probably effective	Hard shoulder running combined with dynamic message signs improve safety **compared to** only **implementing** hard shoulder running. Hard shoulder running combined with dynamic message signs (often termed Managed motorways) improve safety **compared with** just **implementing** hard shoulder running.	[44][45] [78]

Hard shoulder running combined with dynamic message signs (often termed Managed motorways) improve safety **compared with** just **implementing** hard shoulder running.

These, and managed lanes such as slip roads, have brought Intelligent Transport Systems from a *nice to have* add-on facility to an integral part of a road network and they are now an essential tool for a road network operator [22]. The concept behind managed motorways is designed to manage the available capacity even when a collision occurs. While the aim of managed lanes is broadly similar – maintain capacity, reduce environmental impact, and improve safety – the approaches are fundamentally different. For instance, in Australia, managed motorways include ramp signals, lane control, and variable limit signs, whereas in UK, the approach also add extra capacity by additional use of the emergency hard shoulder ('Smart motorways').

Within Europe, managed lanes are mainly found in Western Europe, particularly in metropolitan areas where the strategy of expanding lanes and building new roads has reached its limits. Based on the analysis done by Schönhofer and Bogenberger [21], the common strategies adopted on managed motorways are:

1. Dynamic message signs/Dynamic control signs/Variable message signs – increasingly used
2. Hard shoulder usage – few EU countries but on a relatively large scale
3. HOV lanes – rarely used

Many transport authorities have recognised the potential of managed lane systems, so that a further, significant, increase in projects can be expected in the next few years. Managed lanes are a well-known method in the United States to improve traffic flow, to decrease congestion emergence, and to increase traffic safety. In contrast, in Europe, the term "Managed Lanes" is relatively uncommon, and is commonly perceived as a controlled motorway.

Hard shoulders are a longstanding safety feature of motorways with which the public is familiar. A recent report [77] examined their use as a traffic lane ("dynamic hard shoulder running" (DHS) motorways). A further report [78] shows the risk of a collision between a moving vehicle and a stationary vehicle is higher on motorways that lack a hard shoulder, but the risk of a collision between two or more moving vehicles is lower. This happens because all-lane running is accompanied by technology installed to smooth traffic flow with variable speed limits, enforced by cameras. Messages warning motorists of incidents ahead are displayed on electronic signs. This results in less speeding, less tailgating and fewer rapid changes of speed, because it gives drivers more time to react to conditions ahead. Overall, the evidence shows that in most ways managed motorways are as safe as, or safer than, conventional ones. This has been backed up by very recent data just released[3] and research is ongoing.

All lane running motorways (ALR) ('Smart motorways') have the hard shoulder permanently converted to a running lane. Motorway technologies (for example Stopped Vehicle Detection and alerts on overhead gantries) are applied. Emergency areas provide safer places to stop in case of breakdown or incident. They are safer, if a driver can reach them, than a conventional hard shoulder. If the driver cannot reach the emergency area, then further technology is needed to detect that a vehicle is in a live lane.

The risk of a live lane collision between a moving vehicle and a stopped vehicle is greater on ALR motorways, but the risk of a collision between two or more moving vehicles is lower. Similarly to the case for DHS, this is because ALR motorways have variable mandatory speed limits to smooth traffic flow and electronic signs to warn drivers of incidents ahead. This means less speeding, tailgating, and fewer rapid changes of speed.

The managed motorway safety - evidence stock take and action plan report [78] provide statistical evidence of collision rates and its severity in the UK.

1. Slight casualty rates are higher on controlled (14 per hmvm[4]) and DHS (15 per hmvm), compared to conventional motorways (10 per hmvm), while ALR rates are slightly higher (11 per hmvm).
2. Serious casualty rates on controlled (1.2 per hmvm), DHS (1.2 per hmvm) and ALR (1.3 per hmvm) are slightly higher than conventional motorways (1.1 per hmvm).
3. Fatal casualty rates on controlled (0.07 per hmvm), DHS (0.07 per hmvm) and ALR (0.11 per hmvm) are lower than conventional motorways (0.16 per hmvm).

Given the differences between motorway types in their features, information to users, and degree of control, the profile of incidents and collisions can be expected to vary between motorway types.

6.1.2 SAFEPATH selected measure: High occupancy vehicle lane

Safety performance	Significance	Sources
Probably ineffective – require more real-time pre-post analysis evidence	Safety issues are fewer with concrete barrier separated HOV lanes with no intermediate access points and will be more significant with double-white line separation and many intermediate access points.	[21][25]

[3] https://www.gov.uk/government/news/national-highways-delivers-smart-motorway-safety-upgrade

[4] per hmvm – per 100 million vehicles miles of travel – 160.9344 million vehicle km of travel

High Occupancy Vehicle (HOV) lanes are designed to discourage single or low occupancy car use, by prioritising vehicles with more than a minimum number of occupants (usually two or three), and buses. An example is the measure ‘bus on hard shoulder’ which is seen on multiple routes in the Netherlands. They are designed to encourage car sharing or public transport use by allowing users to reduce their journey times relative to single-occupant vehicles when the general-purpose lanes are congested. The objective of HOV lanes is to increase the average vehicle occupancy and thus reduce road congestion and emissions [21]. More studies are researching the impact of HOV lanes on maintaining traffic flow, but few have quantified their safety impact.

An in-depth investigation was conducted on high occupancy toll lanes (HOT) such as the dedicated HOV lanes, by TUDelft in collaboration with the Rijkwaterstaat centre for Transport and Navigation [25]. They highlighted that physical separation between HOV and the regular lane could influence traffic safety. Vehicle speeds on these dedicated lanes are not allowed to be higher than 20 km/h above the vehicle speed on the regular lanes. Hence, entering or exiting the lanes can cause collisions. They concluded that safety issues are fewer with concrete barrier separated HOV lanes with no intermediate access points and will be more significant with double-white line separation and many intermediate access points. However, there is no real-time pre-post analysis evidence on the benefits of different barrier separation improves safety on highways.

On highways, the only measure that has become established in large parts of Europe is that of dynamic control signs. All other 20 managed lane systems focus on specific countries, depending on the local strategies of the traffic authorities and their technical and financial resources. In contrast to the predominantly static local systems, the systems on motorways and trunk roads are mainly dynamic managed lane systems, which incur higher costs for investment and operation. In general, managed lane systems, especially cost-intensive ones, are concentrated in the western part of Europe, with a particular focus on areas in which, due to the high density of population, cultural activities, workplaces, and goods transhipment nodes, it is impractical to expand the dense road network further.

6.1.3 SAFEPATH selected measure: Mandatory variable speed limits

Safety performance	Significance	Sources
Effective	Injury collisions decreased significantly (-18%), serious and fatal injury decrease by 6%.	[28][29][30]

Variable speed limits (VSL) are integral to the Safe Speeds element of the Safe System Approach. VSLs reduce speeds so that adverse outcomes are reduced in three ways: improving visibility, providing additional time for drivers to stop, and reducing impact forces[5] [20].

Variable speed limits (VSL) are implemented using signs to alert drivers. Sensors along the roadway detect when congestion or weather conditions exceed specified thresholds and automatically reduce the speed limit to slow traffic and postpone the onset of congestion downstream.

Mandatory speed limits mean some form of legislation applies to the speed set and they can be enforced with a fine to speeding drivers, typically via a speed camera linked to the VSL device. VSL that are not mandatory (typically older systems without red borders) are often ignored by drivers.

[5] https://safety.fhwa.dot.gov/provencountermeasures/variable-speed-limits.cfm

VSL can also be deployed in conjunction with dynamic message signs (DMS) to give drivers real-time information on weather or travel conditions. We will explain DMS as part of traffic management in Section 6.1.8 and will discuss a fog warning system in Section 6.1.9. VSL can improve safety by helping to reduce primary and secondary collisions during adverse weather conditions, and congestion. Implementing more uniform driver behaviour and uniform speeds results in less erratic driving overall, reducing the likelihood of collisions. The reduced speeds also help decrease the severity of incidents. This strategy has been successful in Europe but struggles with public acceptance in the USA.

A VSL example: The Netherlands has deployed variable speed limits for weather conditions. Visibility sensors are used to measure the level of fog, and when visibility drops to 459 or 230 ft. (140 or 70 m), the speed limit is dropped to 50 or 37 mph (80 or 60 km/h), respectively. When the speed limit was reduced during fog conditions, drivers reduced their speed by 5.0–6.2 mph (8– 10 km/h). This scheme is not in operation anymore.

6.1.4 SAFEPATH selected measure: Ramp metering

Safety performance	Significance	Sources
Unclear	Few relevant studies found	[55][56]

Ramp metering is the control of a traffic stream from an on-ramp to the motorway [58]. This is done using traffic lights which allow vehicles to enter the motorway one by one or in small platoons. Liu and Wang [55] characterise the ramp metering influence on freeway (motorway/autobahn/snelweg) safety by examining vehicular collisions near on-ramp exits before and after the activation of the ramp metering. They found the average reductions of collisions in the vicinity of an on-ramp exit were around 36%. Although most of the reduced collisions belong to the property damage only category, a 36% reduction shows the significant safety benefit of ramp metering. The traffic congestion induced by each collision, especially during peak hours when ramp metering is in operation, could last for over an hour.

Haule et.al. [56] focused on evaluating the effects of ramp metering on the safety performance of the motorway mainline. They developed a crash risk prediction model for segments downstream of the entrance ramps when ramp metering is activated. The results show that ramp metering could help reduce the crash risk on motorway segments by 12%–14%. However, ramp metering was found to be significant in approximately 42% of the analysed samples. The results also suggested that there were more significant crash precursors when ramp meters were activated than when they were deactivated. Attention should be paid to the effect of the decrease in speed due to the off-ramp metering [58] upon safety on the motorway.

6.1.5 SAFEPATH selected measure: Intelligent traffic control system

Safety performance	Significance	Sources
Probably effective	On average there have been 19% fewer accidents, ranging from 15% to 45%. About 35% fewer secondary accidents	[58]

In intelligent traffic control systems (known as iVRI in the Netherlands, implemented as part of the national Talking Traffic programme) are the traffic lights constantly contact the traffic that passes by and can respond to the current situation. Although traffic lights are not installed on all NRAs' highways, we consider intelligent traffic control systems to be effective tools in highway capacity on those that do install them by improving the efficiency of exits from highways, entrances and connecting roads. On average there have been 19% fewer accidents, ranging from 15% to 45%, with about 35% fewer secondary accidents [58].

6.1.6 SAFEPATH selected measure: Tidal flow operation

Safety performance	Significance	Sources
Unclear	Few relevant studies found	[57][60]

Tidal flow operation may take one of several forms. Some examples are reversible lanes and movable road barriers. Opinions differ on how reversible lanes affect safety. Negative safety effects may be expected for several reasons [60]:

1. Drivers who are not familiar with reversible lanes may choose the wrong driving lane.
2. Reduced congestion may lead to increased speed.
3. When reversible lanes are installed on motorways and the median barrier is removed, head-on collisions may increase.
4. Lane changes and turning movements at at-grade junctions may get more complex.

Factors that may contribute to positive safety effects, or at least to abate possible negative safety effects, are:

1. Reversible lanes may remove traffic from the local road network to the safer network of main roads and motorways.
2. Many drivers on the main road network during peak congestion times are using the same routes daily and will soon become familiar with reversible lanes. When there is much traffic, drivers tend to follow the vehicle ahead, which reduces the risk of choosing the wrong lane. A possible increase of accidents immediately after the installation of reversible lanes may therefore not be long-lasting and may even be followed by a decrease in the number of accidents.
3. The cost to efficiently control reversible lanes and the confusion of drivers [57].

Reversible lanes are more unsafe as there is a potential for confusion among road users. This can be mitigated using movable barriers, such as the 'zipper' on San Francisco's Golden Gate Bridge, as they reduce the possibility of a head-on collision and possible crossovers [58].

The specific effectiveness tidal flow operation depends on the design and on local factors.

6.1.7 SAFEPATH selected measure: Lane redesign and adjustments

Safety performance	Significance	Sources
Unclear	Implementation of 2+1 roads appears to reduce severe and fatal injuries, but not enough relevant studies found	[50]

Changes in the design of lanes can be made so as to realise higher capacity. 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, 2+1 roads with median barrier are found to reduce the rate of severe and fatal injuries by about 51-63 %, depending on the road type and speed limit [50]. The effect on rates of less severe injuries is smaller and, in some cases, not significant. The reviewed studies are limited in number, so the results should be interpreted with care. The effect of 2+1 roads without a median barrier is not clear.

The results of implementing of 2+1 roads with cable barrier in the median are summarised as [50]:

1. Reduces the rate of severe and fatal accidents on rural roads by approximately 50-60 %
2. Has an uncertain effect on the rate of less severe injuries. Estimates range from +8 % (not significant) to -29%.
3. Appears to be effective in reducing accidents on links (road sections between intersections/ junctions), but less so at intersections/junctions.
4. Appears less effective in reducing injury rates on roads with higher speed limits (110 km/h) than on 90 km/h roads. It is, however, not clear whether this difference is statistically significant.

Lane modifications provided a capacity measure to reduce the ambiguity for road users [58]. In Sweden, due to 2+1 roads, the total number of fatalities was reduced by 76% from 228 to 54 people killed. The Netherlands implemented tapering in lane merges, especially in a 2+2 configuration. With tapering in the Netherlands, no significant difference in safety was observed.

6.1.8 SAFEPATH selected measure: Traffic and route information

Safety performance	Significance	Sources
Probably Effective	Variable Message Signs (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.	[50][58]

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 investigate drivers' behavioural adaptations to the VMS rather than the effect on crashes.

VMS allow a range of information to be conveyed to road users. They are used as an alternative to purpose-built advance motorway condition information signs (AMCIS) and motorway condition information signs (MCIS). These advanced alternatives are intended to assist drivers in making route choices before entering the motorway. The range of information goes beyond travel time and traffic conditions and can include warnings of hazards or disruptions with details of actions to take (e.g., merge left), or forthcoming events affecting motorway travel. Signs that have been used include variable displays (sometimes embedded in direction signs) indicating motorway traffic conditions as light/medium/heavy, or as travel times in minutes to specific destinations; in addition, sign displays may be colour coded e.g., green means light traffic, red means heavy traffic.

According to Motorways 2018 [40], VMS are particularly useful where there is limited visibility, for example in tunnels. Table 8 briefly describes the benefits over critical collision factors.

Table 8: Variable message signs benefits

Collision cause	Benefits

Limited sight distance in motorway tunnels	Supply the driver with information concerning the current traffic situation.
Too fast in unexpected sharp bends	VMS signals the danger of the bend after analysing the Vehicle's speed.
Speeding	Speed limits are presented to the driver under special environmental circumstances.
Insufficient safety distance	VMS warning – fog/weather warning system.

The benefits, limitations, and recommendations for VMS is highly influenced by the CEDR report, 2012, ASAP[6] and BRoWSER[7] projects.

Only one study investigated the effects of VMS on collisions [61]. 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 investigated the behavioural effects of VMS, either on the road or in a driving simulator experiment [62]. It was found that VMS location and information format have a major influence on the resulting behavioural adaptations of drivers.

Traffic and route information have indirect impacts on safety due to the resulting reduction of rear-end collisions [58].

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

6.1.9 SAFEPATH selected measure: Fog warning system in combination with VMS

Safety performance	Significance	Sources
Probably effective	Fog warning systems can be used to dynamically set the speed limits.	[63][58]

Fog warning systems can be used to dynamically set the speed limits. Although the number of empirical results is limited, the available literature shows that dynamic speed limits have favourable effects on driving speeds and on the number of crashes.

Fog warning systems improve the safety on roads, as they generally result in drivers reducing speed, and a reduction of speed by 5kmph reduces the number of accidents by 15% [63]. Traffic and route information has indirect impacts on safety due to the reduction of rear-end collisions [58].

6.2 SAFEPATH road user behaviour measures

Three road user behaviour capacity measures with strong evidence base were identified in earlier SAFEPATH research. An analysis of their impact on road safety is given below.

[6] http://asap.fehrl.org/

[7] http://browser.zag.si/

6.2.1 SAFEPATH selected measure: Speed enforcement using speed cameras

Safety performance	Significance	Sources
Effective	The pre/post reductions ranged from 8% to 49% for all collisions and 11% to 44% for fatal and serious injury collisions.	[26][27]

Speed cameras are enforcement tools to register speeding offences and identify vehicle owners based on the vehicle registration number. Based on the SWOV (SWOV is the national scientific institute for road safety research in the Netherlands) fact sheet [13], personal injury collisions are reduced by approximately 20% in on road sections where cameras are used. A study by Wilson et al. [26] reported an absolute reduction in average speeds post-intervention of speed cameras.

The following guidelines indicate the criteria for whether and where speed cameras should be used:

1. where there is a relatively high number of collisions.
2. where there is an apparent, or plausible, connection between collisions and speed.
3. where there is a relatively high percentage of speed offenders.

The Traffic Enforcement Team has introduced guidelines for placement and usage, as well as replacement of analogue fixed cameras by digital ones [18].

The traffic safety effects of 65 fixed speed cameras, installed between 2002 and 2007, on highways in Flanders-Belgium, are evaluated by de Pauw et al [71], who carried out a before and after study with control for the trend. The analyses showed a non-significant decrease of 8% in the number of injury crashes. In the case of the more severe crashes with serious and fatal injuries, a decrease of 29% was found, significant at the 5% level. De Pauw et al conclude that speed cameras have a favourable effect on traffic safety, mainly with respect to severe crashes. The twenty-six studies were evaluated for a pre/post reduction in the proportion of speeding vehicles [58]. Near camera sites, these pre/post reductions ranged from 14% to 72% for all collisions, 8% to 46% for injury collisions, and 40% to 45% for collisions resulting in fatalities or serious injuries. However, in the workshops it was mentioned that speed cameras may cause driver distractions as drivers are constantly using speedometers to keep track of their speeds.

Gaps:

The reasons behind deploying speed cameras, and with that also the set-up and use of camera systems, turn out to be different in different counties. Belin et al. (2010) [18] examined the policy vision behind the deployment of speed cameras in the Victoria (Australia) and Sweden. In Sweden, the idea is that there is a conflict between the road design and the speed of the road user, and that camera programs should be limited only to dangerous locations and should contribute to creating a social norm amongst road users that it is easier and safer to keep to the speed limit. Australia, on the other hand, works from the thought that continuous and intentional violation of the speed limit by drivers is the problem.

Through increasing the objective chance of being caught and intensive information campaigns, road users should get the idea that they can be checked for speed at any time and at any location. Sweden attempts to convince road users through providing information on safe speed limits; Australia attempts to influence road users more through mechanisms of general and specific deterrence.

This makes direct comparison a challenge.

A before-after analysis approach with pre- and post-implementation periods ranging from two to eight years in the UK found a decreasing trend in KSI collisions after the installation of average speed enforcement, ranging from 33% to 85% [58]. Reductions in minor injury collisions were also noted across several evaluations. Average Speed Enforcement Cameras (ASECs) are considered safer than spot speed cameras as they do not encourage instant braking and acceleration, rather they help in harmonising the speeds along the enforced route.

Highlights:

Speed cameras resulted in a reduction of approximately 20% in personal injury crashes on road sections where cameras are used [13].

The DaCoTa project from 2012 [86] formulated ten 'golden rules' for setting up successful speed enforcement through cameras (as well as stopping drivers).

Different perception: Sweden attempts to convince road users through providing information on safe speed limits; Australia attempts to influence road users more through mechanisms of general and specific deterrence.

6.2.2 SAFEPATH selected measure: Driver training and education

Safety performance	Significance	Sources
Probably Effective	GDL and FPLT appear to reduce crash rates and, to a small extent, improve driving behaviour.	[51][58]

All the measures related to driver training and education had a positive impact on safety [58]. The safety campaigns inform road users about dangerous behaviour like driving too close to each other or drinking alcohol, which results in higher compliance with rules.

It is reported [51] that the 34 reviewed studies focused on the effect of the graduated driver licensing (GDL) and formal pre-license training (FPLT) on learner and novice drivers' road safety (four meta-analyses and thirty original papers). The results of the studies tend to indicate that GDL and FPLT have a global positive effect on road safety, but some inconsistent results were noted regarding drivers aged 18 and above. More specifically, GDL and FPLT appear to reduce crash rates and, to a small extent, improve driving behaviour. However, these effects are sometimes reversed for older drivers.

The mixture of significant improvements, one significant reduction in desired behaviour and nonsignificant results along with the variety of education/training and assessment methodologies makes it challenging to draw clear conclusions.

6.2.3 SAFEPATH selected measure: Dynamic speed display signs

Safety performance	Significance	Sources

Probably Effective	Results consistently show that dynamic speed display signs have favourable effects on speeds. One study calculated the effect on the number of crashes and found a significant overall reduction of 5%.	[51][64][65]

These are often temporary speed signs that warn drivers they have exceeded the speed limit by showing them their current speed dynamically, or for example a green "smiley" face along with their measured speed. They have been used on NRA roads where fuller speed cameras or variable speed limits are not suitable.

An overall reduction in the number of crashes of 5% was observed due to dynamic speed display signs (DSDSs). Results consistently show that DSDSs have favourable effects on speeds [58].

The results of the analyses indicate that DSDSs are effective in reducing free-flow car speeds while in place and activated [64]. However, the speed reductions observed while the DSDSs were in place disappeared within a few weeks after the devices were removed from the study sites.

Reviewed studies in the literature consistently report significant decreases of mean speeds due to the presence of active DSDSs, although the size of the effect varies [51]. The results of 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.

Hallmark et al. [65] calculated the effect on collisions by means of a before-and-after study. They found an overall reduction in the number of collisions of 5% (CMF 0.95) with a 95% CI [0.93-0.97].

6.3 SAFEPATH vehicle technology measures

Three vehicle technology capacity measures with strong evidence base were identified in earlier SAFEPATH research. An analysis of their impact on road safety is given below.

6.3.1 SAFEPATH selected measure: Intelligent speed adaptation

Safety performance	Significance	Sources
- Unclear	The studies have good levels of quality and consistency. However, there are several results which cannot be strongly supported due to lack of statistical tests	[52][66]

Intelligent Speed Adaptation (ISA) can be implemented either passively by alerting the driver to excessive speed via a visual, auditory and/or tactile cues and allowing the driver to alter their speed themselves, or actively, where the vehicle intervenes and automatically reduces the speed to within the legal/safe limit.

The effects of speed adaptation devices in cars are mostly positive in reducing collision frequency, vehicles' mean speed and drivers exceeding the speed limit [52]. The studies in this report encompass several topics and have good levels of quality and consistency. There were cases, however, where findings did not include any statistical tests, and therefore conclusions cannot be strongly supported. The results seem generally transferable with caution.

Theofilatos et al. [66] provide an overview of the effects of selected Advanced Driver Assistance systems (ADAS), namely intelligent speed adaptation, collision warning and alcolock on driving behaviour and road safety. Results indicate that in-vehicle technologies have the potential of playing an important role for improving road safety. However, there is lack of both quantitative and qualitative reviews because relevant research is relatively limited.

None of the studies on ISA was sufficiently large to provide evidence demonstrating safety improvement [58]. Indeed, it is likely that the true effects of ISA will only emerge when a larger percentage of vehicles equipped with ISA is being used.

Some negative aspects of ISA were reported in many studies [58]. These include direct effects such as driver distraction and indirect effects such as behavioural adaptation. Any activity that distracts the driver or competes for their attention while driving can potentially degrade driving performance and thus have serious consequences for road safety. Thus, careful consideration is needed when deciding on the nature and positioning of in-vehicle warnings and displays.

6.3.2 SAFEPATH selected measure: HGV platooning

Safety performance	Significance	Sources
- Unclear	Few relevant studies found.	[67]

Platooning, in which an “electronic towbar” is used to connect at least two but maybe more vehicles together so that the lead vehicle’s driver determines the vehicle speed. Technology then closely links the remaining vehicles so they are a co-ordinated convoy.

When considering platooning, a more detailed reporting of incidents regarding the systems, the driver and the interaction with the environment is desirable. Asare et al. [67] proposed twelve safety performance measures for truck platooning. These were: rates of collisions, near-collisions, safety critical conflicts, the number and types of system failures, the conditions under which they occur, failures to notify the drivers about loss of control, V2V signal loss, disengagement of the driver, episodes and levels of fatigue, levels of vigilance and distraction of the driver, cut-ins by other vehicles.

Overall, the potential for road safety due to platooning stands and falls with the reliability of the implemented ADAS and its proper use by operators. Based on these assumptions, platooning could substantially contribute to safer HGV traffic.

Most research shows that truck platooning brings improvements in traffic safety [58]. As deployed in the HelmUK trials, platooning is as least as safe as ACC despite travelling at half the headway and is unlikely to introduce new collision types. The systems required for platooning operations, such as LKA, offer additional safety improvements regardless of whether platooning is operational or not. The ENSEMBLE project[8] highlights platooning enables a faster reaction to potentially dangerous braking situations because of V2V communication.

[8] https://platooningensemble.eu/project

Platooning may, however, lead to extra risks in certain situations such as highway on-off ramps.

Gaps:

There is incomplete understanding of where the optimal type of road geometry to safely enable platooning might be found- the UK for example has junctions too close together for effective platooning, while other nations have very long junction-free sections. Also, the extent to which fuel and hence emission savings from platooning are higher than that from unsafe following distanced often chosen by drivers is unclear.

6.3.3 SAFEPATH selected measure: Green light optimised speed advisory (GLOSA)

Safety performance	Significance	Sources
- Probably effective	Studies show that the introduction of the GLOSA system eliminated the need for sudden rapid deceleration in the vicinity of the intersection	[58][68]

It is reported [68] that GLOSA system increased the time headway of vehicles and decreased the need for deceleration in the vicinity of the signalised intersection. In addition, a partial increase in fuel efficiency was produced using GLOSA system without affecting vehicle travel time. Thus, GLOSA system can achieve safer traffic flows in the simulated real-world signalised intersection without deteriorating the traffic flow efficiency.

Studies show that the introduction of the GLOSA system eliminated the need for sudden rapid deceleration in the vicinity of the intersection. Therefore, it can be stated with confidence that the use of the GLOSA system would result in safer intersection traffic flows in signalised intersections [58].

6.4 SAFEPATH incident response measures

Four incident response capacity measures with strong evidence base were identified in earlier SAFEPATH research. An analysis of their impact on road safety is given below.

6.4.1 SAFEPATH selected measure: Faster response to incidents

Safety performance	Significance	Sources
Effective	The proper road design and deployment of TIM resources can positively influence the impact assessment. As a result, faster and improved incident detection can decrease the duration of collisions and motorway closure.	[41][43]

Post-crash (trauma) care or trauma management is one of the pillars of Vision Zero [41][43]. It refers to the medical treatment provided after a collision, whether administered at the scene, during transportation to a medical centre, or subsequently. Effective post-crash care, including fast transport to the correct facility by qualified personnel, reduces the consequences of injury. Research indicates that reducing the time between the collision and the arrival of emergency medical services from 25 to 15 minutes could reduce deaths by one-third. Moreover, systematic rescue and ambulance teams training may reduce the extrication time of trapped car and truck collisions victims by 40-50 %. Post-crash care incorporates elements related to emergency services and medical care, crash reporting and investigation, traffic incident management, and the justice system. Based on the project's scope, we will elaborate on the organisational aspects of traffic incident management that influence capacity.

Traffic Incident Management (TIM) is a structured strategy for dealing with road traffic incidents. The strategy involves developing joint working practices between national road administrations, the police, and other incident responders to ensure the mutual objectives, including the safety of both road users and responders, are achieved. The main goal of TIM is to manage and resolve incidents in a safe, effective, and quick way [42]. The report "Best practice in European Incident Management," published by CEDR in 2011, highlighted the benefits of efficient incident management integrated with dynamic traffic management tools that can optimise the capacity use of the road system. The CEDR TNM WG Fact Sheet on Incident Management [79] published the experiences of countries where TIM has been in operation for several years. Based on the evidence, the TIM contributes significantly to:

- reduced delays
- improved journey time reliability
- increased safety of responders and public
- reduced risk of secondary incidents
- freeing of police for non-traffic duties
- better incident logging and statistics

The proper road design and deployment of TIM resources can positively influence the impact assessment. Faster and improved incident detection can decrease the duration of road closure following collisions, so maintaining highway traffic flow efficiency. This has been found by evaluation studies [79] performed in Austria, Denmark, and the Netherlands. Other impacts of effective TIM include a decrease in secondary incidents upstream of the incident location and increased safety for road users and road incident handling and clearance site teams.

More information on incident management case studies and guidelines, reference studies and reports can be found in the following links:

- Annex of EasyWay Incident Warning and Handling Deployment Guidelines: http://dg.its-platform.eu/DGs2012 [87]
- CEDR T13 Final Report on Best Practice in European Traffic Incident Management, 2011, https://www.cedr.eu/docs/view/60632105320e1-en
- International Benchmarking Study of Traffic Incident Management, 2018, Danish Road Directorate
- FHWA (2010) Traffic Incident Management Handbook: https://ops.fhwa.dot.gov/eto_tim_pse/publications/timhandbook/tim_handbook.pdf

In this context, the EU Commission is closely monitoring the effects of the roll-out of emergency Call (e-Call), the automated emergency call in the event of a crash.

Gaps:

Effective coordination and cooperation between emergency services establishes a successful TIM. However, there are critical gaps and challenges encountered in this area. A study done in the Netherlands, which is by far one of the safest countries in the world, highlighted the challenges still been observed in establishing an effective TIM [11]. The main problems related to information sharing, communication, and coordination have been identified as the main bottlenecks for effective cooperation between emergency services (e.g. Comfort *et al.*, 2004; Chen *et al.*, 2008). Historically, each organization has developed information systems which are primarily designed as closed systems which mainly support their own specific IM tasks. Even within organizations there are still many problems in terms of system diversity, architecture, and standards used. However, organizations are starting to realize that introducing new interoperable system concepts forms an important constraint for significantly improving cooperation. One of the interoperable solutions is to support information-sharing between public and private emergency services and road authorities.

6.4.2 SAFEPATH selected measure: Access to emergency services

Safety performance	Significance	Sources
Effective	The earlier the scene can be cleared, the fewer odd manoeuvres you get, which has a positive effect on road safety.	[41][43] [58]

Direct access to emergency services has a positive effect on road safety [58]. For example, several places do not have matrix boards that can automatically signal a lane closure. As a result, arriving at the accident scene earlier and securing the scene will have a major effect on road safety. At every accident people driving by tend to make unpredictable manoeuvres around the accident (for example due to nervousness), which has a negative effect on road safety. The earlier the scene can be cleared, the fewer such manoeuvres result, which has a positive effect on road safety.

6.4.3 SAFEPATH selected measure: Incident detection

Safety performance	Significance	Sources

Effective	Most of the studies and implementations report an increase in safety due to incident detection systems.	[41][43] [58] [60]

Most of the studies and implementations report an increase in safety due to incident detection systems. In an emergency, every second counts. The reduction of emergency management time leads to an increase in safety [58].

There are several factors that can be assumed to affect the effectiveness of automatic crash notification (ACN) [60]. The effects can also be assumed to be related to the response times and the adequacy of the medical treatment provided. When response times are long, shorter notification times may be of limited value since the most serious injuries require treatment within one hour at a maximum. When no adequate treatment is provided, shorter notification times may also be of limited value. Measures that reduce the type of serious accidents in which ACN is most beneficial are likely to reduce the effectiveness of ACN in terms of the total numbers of lives saved.

6.4.4 SAFEPATH selected measure: Institution cooperation

Safety performance	Significance	Sources
Effective	Quicker reactions in incident management, faster information chain and better situational awareness led to improvements in traffic safety	[41][43] [58]

More rapid incident management, faster chains of information and better situational awareness led to improvements in traffic safety [58].

6.5 SAFEPATH regulation measures

Two regulation capacity measures with strong evidence base were identified in earlier SAFEPATH. An analysis of their impact on road safety is given below.

6.5.1 SAFEPATH selected measure: Congestion pricing scheme

Safety performance	Significance	Sources
Probably effective	In the UK, the accident rate fell by 22% after the implementation of this policy due to fewer vehicles on the road.	[58]

In the UK, the accident rate fell by 22% after the implementation of congestion pricing [58]. The probability of having an accident in Central London fell due to the reduction in traffic congestion. Thus, by reducing congestion, the pricing saved lives both by moving people out of cars and by making the commute safer for those who continued to drive.

6.5.2 SAFEPATH selected measure: Overtaking ban for HGVs

Safety performance	Significance	Sources
Effective	According to a study of a sample of accidents involving HGVs (European Commission, 2007), accidents after an overtaking or lane-changing manoeuvre accounted for 11.3% of all HGV accidents.	[50][58]

There were reported changes in traffic behaviour that could affect accident risk [58]. For example, less frustration for car drivers and more homogenous traffic flow could result in a lower accident risk. According to a study of a sample of accidents involving HGVs [80], accidents after an overtaking or lane-changing manoeuvre accounted for 11.3% of all HGV accidents.

HGV lane restrictions can affect road safety positively by improving traffic flow and reducing overtaking by HGVs [50]. HGV lane restrictions result in reduced speeds and accident numbers [50], both in the lanes concerned and in neighbouring lanes. This topic has been studied across a limited number of conditions and so far only in the USA, so the transferability of the results may be limited, but in general results appear to show that HGV lane restrictions are overall an effective capacity measure.

7 System modelling for analysing safety impact of a capacity measure

In this work package, we developed a safety impact analysis model which is based on work carried out in WP2000 and WP3000. In WP2000 a systems diagram was developed to provide a basic conceptual model for the system of highway capacity and traffic safety, and in WP3000 capacity measures that have been implemented across various countries are listed.

7.1 Approach

Within Work Package WP2000, a systems analysis approach was chosen, which helps understanding the "system" and provides a systematic way to analyse the effect of different "means" and "measures" on highway capacity and road safety. In WP4000, we follow a similar approach to develop the model for safety impact analysis of capacity measures.

The process of developing a systems model for safety impact analysis of capacity measures involved 4 steps:

1) Determining the capacity measures. For the first step, the capacity measures determined in WP3000 are used. In WP3000, a detailed list of good practice measures and interventions is collated. Readers are advised to consult the report of WP3000 for more details of the capacity measures.

2) Specifying the criteria. The second step involves identifying the criteria. In WP2000, because of the objective tree analysis, six criteria were identified: congestion severity, traffic flow, delays, travel time reliability, collision risk, and collision severity. Collision risk and collision severity are used in the safety impact analysis model. They provide a set of reliable KPIs to measure the safety effect of different capacity measures and to continue with further steps of the systems analysis.

3) Identifying influencing factors and mapping out casual relations. The third step is to identify the factors that influence the criteria identified in step two and map the causal relations among these factors. The details of this step are provided in Section 7.2. The outcome of this step is the causal relation diagram which provided insight into how different factors influence each other and the criteria.

4) Creating the systems model. In the last step, the findings from the first three steps were combined to gain a full overview of the system. The details of this step are provided in Section 7.3.

The systems diagram is the main product of WP2000 and forms the basis for further analysis within this WP4000. The diagram expresses the DoRN in a systematic model and explains the influencing factors, means, and criteria. Readers are advised to consult the report of WP2000 for more details regarding the outputs of systems analysis.

7.2 Identifying influencing factors and mapping out casual relations

The factors identified in Section 4.3 were put together with their relations to form the causal relation diagram.

This diagram provides an overview of the relevant factors in the problem analysis. The relationships between different factors are also indicated, as either positive or negative. A positive relation means that a change in one factor will cause a change of the same direction in another factor. In other words, an increase (or decrease) in one factor causes an increase (or decrease) in another factor. A negative relation indicates that an increase in one factor causes a decrease in the other factor, and vice versa.

The causal relation diagram for the safety impact of safety risk factors on collision risk and collision severity criteria is shown in Figure 5.

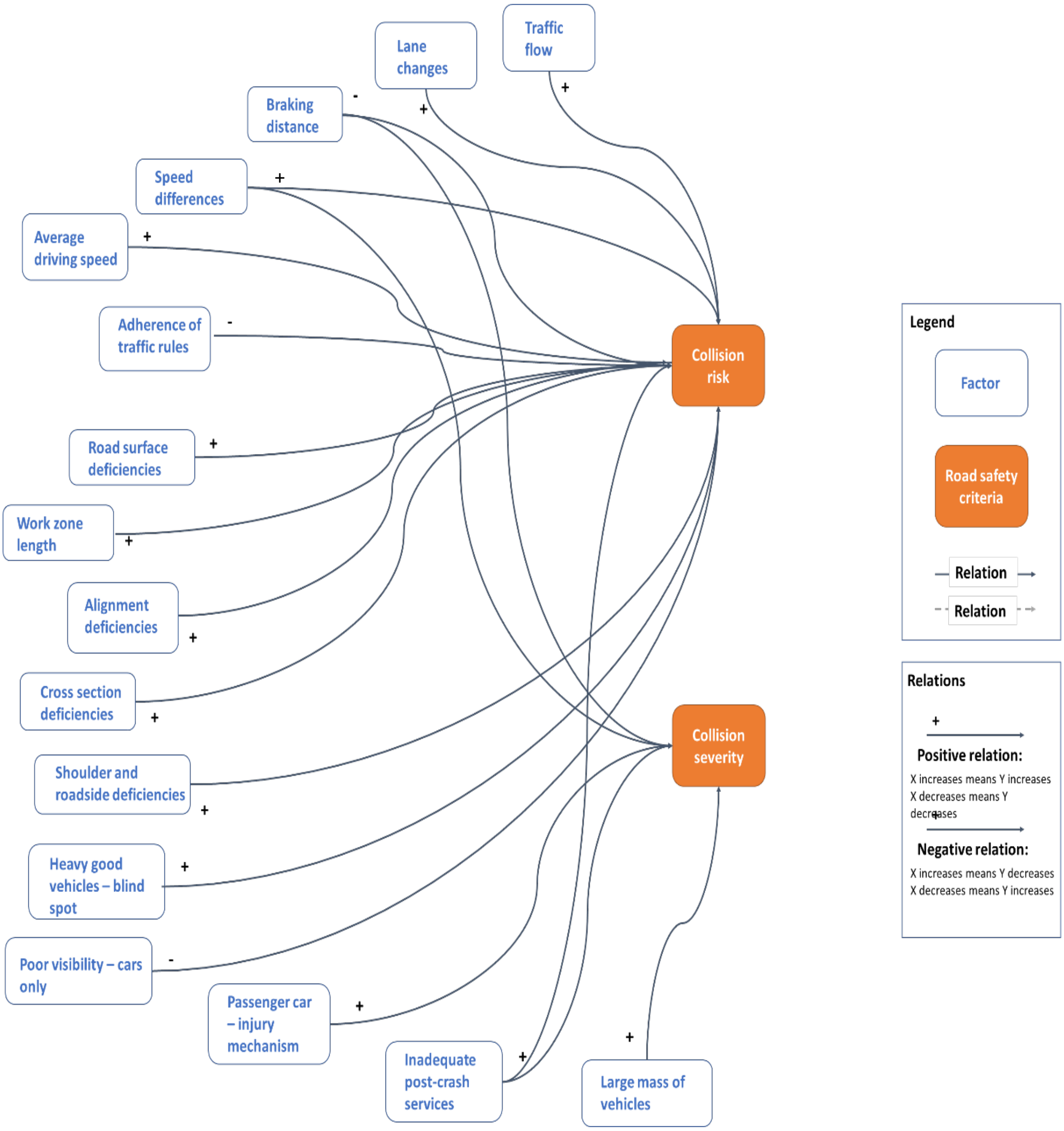


Figure 5: Causal relation diagram for safety impact of safety risk factors on collision risk and collision severity criteria

The causal relation diagram provides details on how several factors influence criteria directly. Table 9 provides the description of various relationships within the causal relation diagram.

Table 9: Relationships between different factors in causal relation diagram

Road safety criterion	Influenced by	Relation
Collision Risk	*Braking distance*	*Negative*
	Traffic flow	*Positive*
	Adherence to traffic rules	*Negative*
	Speed differences	*Positive*
	Lane changes	*Positive*
	Road surface deficiencies	*Positive*
	Work zones length	*Positive*
	Horizontal alignment deficiencies	*Positive*
	Cross-section deficiencies	*Positive*
	Shoulder and roadside deficiencies	*Positive*
	Visibility – Darkness (cars only)	*Negative*
	Heavy goods vehicles – risks resulting from the blind spot issue	*Positive*
	Average driving speed	*Positive*
	Inadequate post-crash services	*Positive*
Collision Severity	*Speed differences*	*Positive*
	Average driving speed	*Positive*
	Mass of vehicle(s)	*Positive*
	Passenger car – injury mechanism - risk of injury	*Positive*
	Inadequate post-crash services	*Positive*

These were not the only factors to influence the system. However, for simplicity and comprehensibility of the diagram, those factors were not included in the causal relation diagram. The model can be extended with several other factors which are also relevant.

7.3 Overview of the model

Figure 6 shows the safety analysis model that we developed to estimate the safety impact of capacity measures.

There are four main elements in the diagram:

- **Highway capacity measure** (on the left side) are the capacity measures which can influence the safety of the highways.

- **Road safety criteria** (on the right side) are the factors whose values indicate the degree of influence and quantify the safety impact.
- **External factors** (on the top) are the factors which cannot be influenced by any means.
- **Internal factors** (in the centre) are the factors affected by highway capacity measures, which affect the road safety criteria.

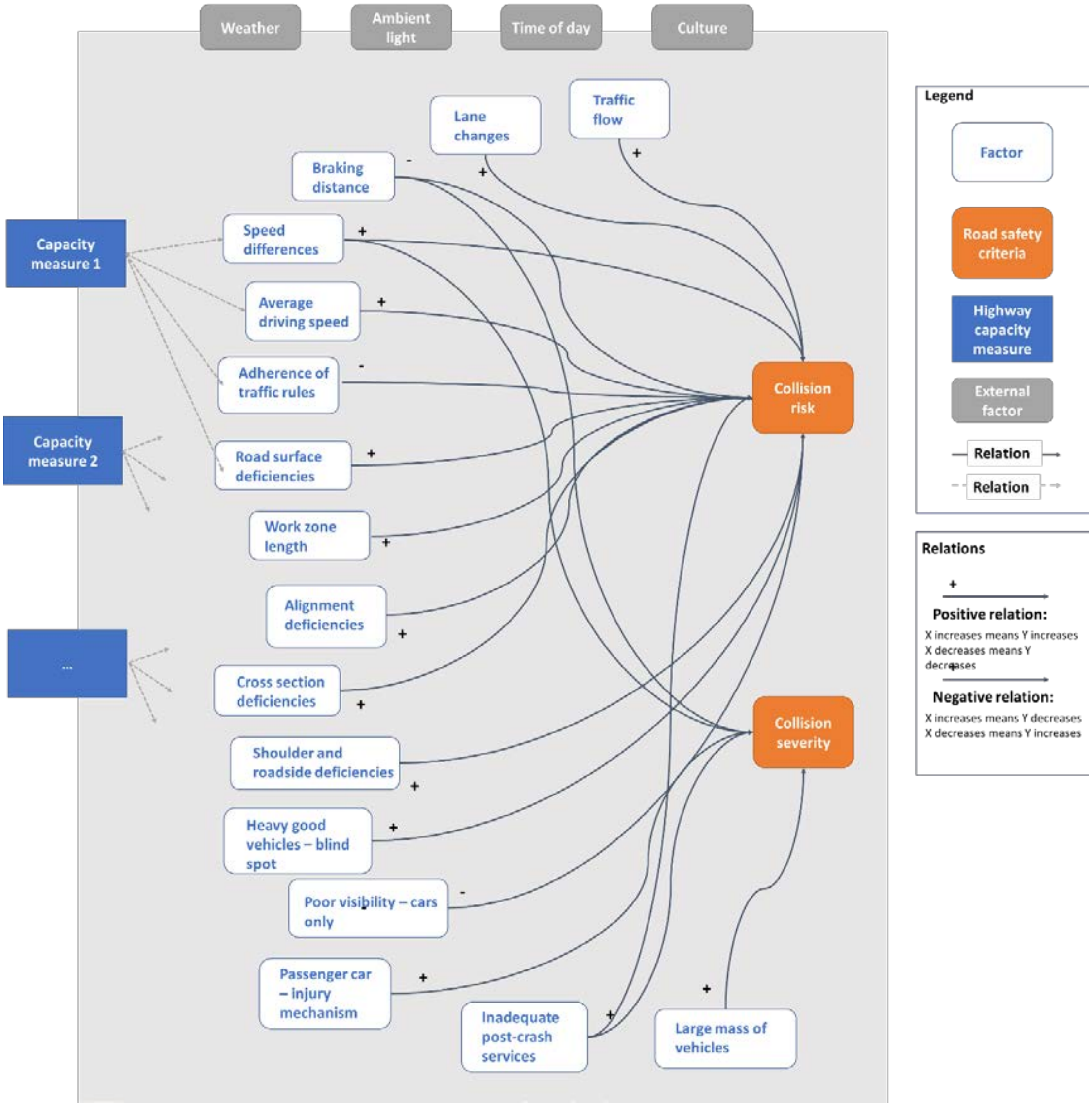


Figure 6: System model for analysing safety impact of capacity measures

Using this model, it can be predicted whether the safety impact of a capacity measure will be positive or negative.

This model facilitates as an indicator on how different measures affect different criteria. This is done with the help of causal chains. In addition, the factors which need to be influenced to achieve an objective can be determined with the help of this model.

The proposed model reflects the theoretical potential of measures to address risks. Only the existing evidence in the literature can give the final answer as regards the strength of each link between a risk and a measure.

Interpretation of the Systems Model

The model presented in Figure 6 provides a clear structure through which one can understand the system of highway capacity and road safety and the various relationships between different factors. This information is used to ascertain how different capacity measures influence the system.

The dashed arrows in the system diagram indicate that a capacity measure directly influences a particular factor. Dashed arrows can take a positive or negative direction, depending upon situation.

The systems diagram can be read in many ways. It is, however, recommended to study the system by starting from the capacity measures. The following example shows how one can read a small part of the systems diagram. The rest of the diagram follows the same principle.

Example:

We can consider “Mandatory variable speed limit” capacity measure to increase infrastructure capacity as discussed in Section 6.1.3. In this case, the user aims to analyse the safety impact of implementing the “Variable speed limit” capacity measure. This measure influences the three factors average driving speed, adherence of traffic rules and speed differences. User sets the relations between the capacity measure and the safety factors. Looking at the relations diagram, a variable speed limit decreases the average driving speed and speed differences and increase adherence of traffic rules. This in turn leads to lower collision risk and collision severity in this scenario. As a result, the “Variable speed limit” capacity measure will have an indication of positive safety impact.

8 SAFEPATH impact indicator tool

Using the model presented in Section 7, we developed the SAFEPATH Impact Indicator Tool (SAFEPATH-IIT) that aims to support users on the analysis of safety impact of capacity measures, complementing this report. The tool is developed using Microsoft Excel software and is used by running the file *SAFEPATH-IIT.xlsx*. It contains the capacity measures with an overview of their impact on highway safety, and other factors. The information collected from workshops, existing studies, and the literature review is stored in *SAFEPATH-IIT.xlsx* file.

The tool enables easy access to the information collected during road safety analysis research and can be used to gain more insights about the safety impacts of capacity measures. The tool also helps users by giving indications on the safety impact of each capacity measure.

This section provides an overview of the functions of the tool and presents information on usage of the tool.

8.1 Overview of SAFEPATH-IIT

The goal of the tool is to indicate how a capacity measure can influence road safety. Users can view and explore the capacity measures and safety factors, allowing them to get an indication on how different capacity measure influence safety factors.

SAFEPATH-IIT implements the system analysis model presented in Section 7 and can be used to gain more insights about safety impact of capacity measures on safety risk factors. During the tool's design phase, the design team received multiple feedback and suggestions. These helped to make the tool more intuitive, with a key focus on the user needs.

As the main purpose of the tool is to provide an indication of the safety impact of capacity measures, a set of functionalities is provided to enable users to explore the content and extract the information they need. The tool allows users to select a capacity measure from a drop-down list based on WP3000. It also features a table which enables users to look for a specific capacity measure and examine its impacts on safety risk factors according to the results of this study. The results page displays the safety performance indicator values of the selected capacity measures.

A built-in decision mechanism (Appendix A) computes the safety performance indicator value of the capacity measures. These features aim to make the SAFEPATH-IIT a powerful, easy to use and intuitive tool which provides a systematic way to analyse the effect of different capacity measures on highway safety.

There are three sheets in the tool:

- The first sheet (*UserInput*) presents the relations between capacity measures and safety risk factors. The user can input the capacity measure to be analysed and examine the capacity measure's effect on the safety risk factors.
- The second sheet (*SafetyImpactResults*) displays an indication of the impact of the capacity measure on road safety. The user can use this sheet to analyse and compare the safety performance indications because of the impact values set in the first sheet of the tool.
- The third sheet (*ImpactOfCMsOnRiskFactors*) provides a table with all the capacity measures and safety risk factors. The information collected from workshops, existing studies, and the literature review on how a capacity measure influences capacity measures is captured in this table. The user can examine the effects of different measures on different risk factors. They

can also change the values in this table to analyse how these changes affect the safety performance indicator value. The values in this table are used to populate the impact values in the input sheet.

The *UserInput* sheet of the tool provides an interface for the user (Figure 7). This contains the following elements:

A. A set of safety risk factors
B. A set of capacity measures which can be selected by the user from a drop-down list
C. The impact of a capacity measure on a safety risk factor. A capacity measure can have an impact of *increase*, *decrease*, or *no effect* on a risk factor.

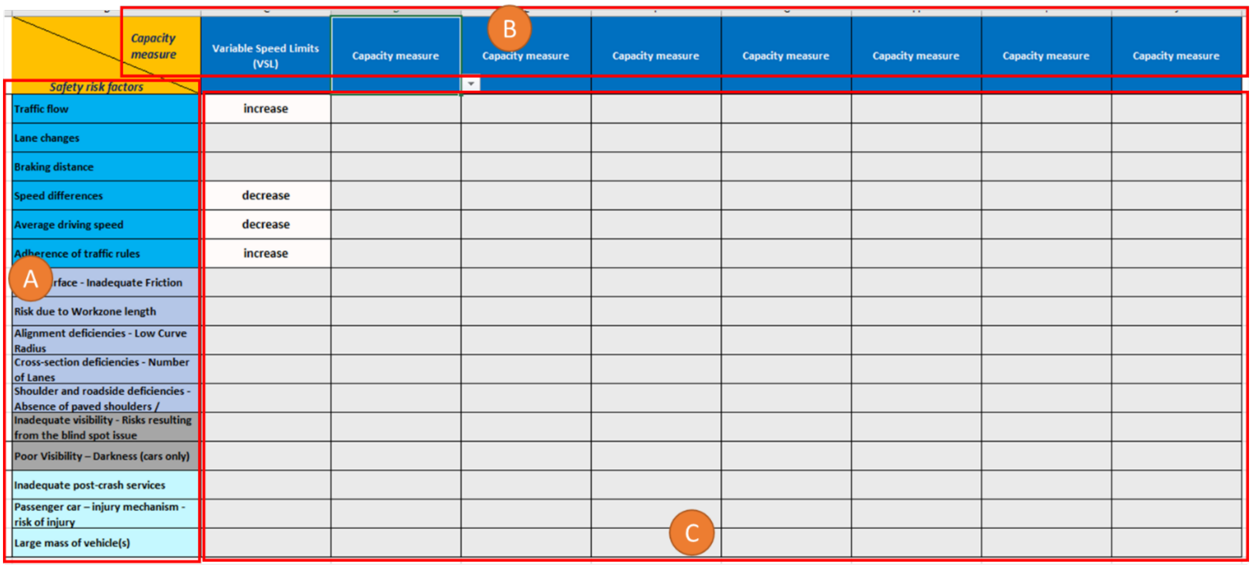


Figure 7: User input sheet of SAFEPATH-IIT

When the user selects a specific measure, the safety impact values for that measure are displayed on the user input sheet *Area C* (Figure 7). These impact values are automatically extracted from the sheet named *ImpactOfCMsOnRiskFactors* (Figure 8).

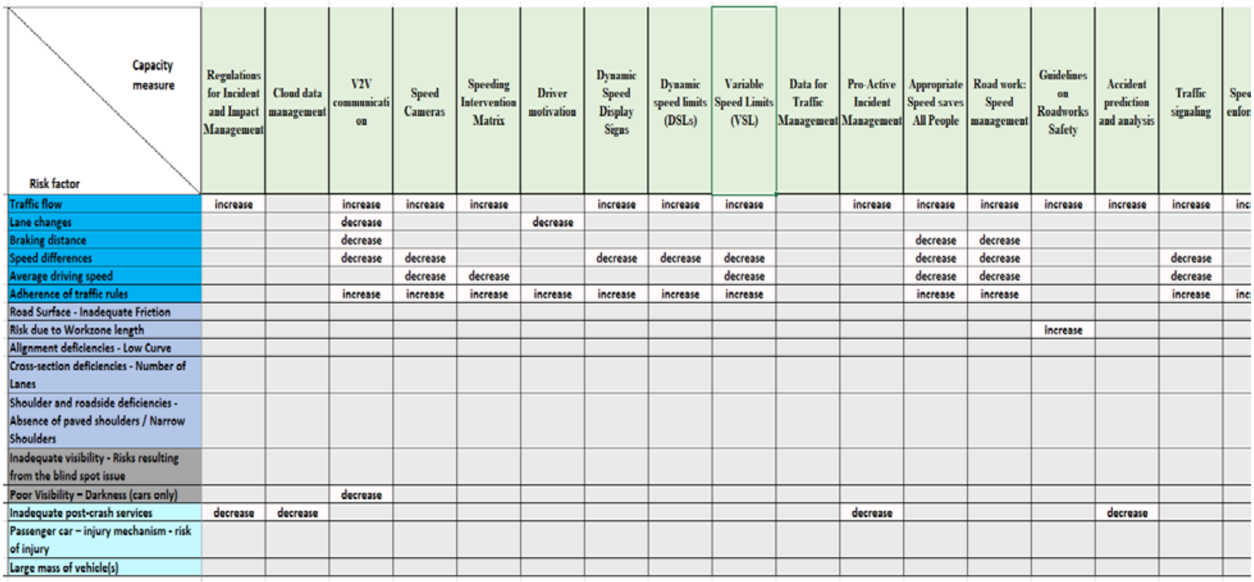
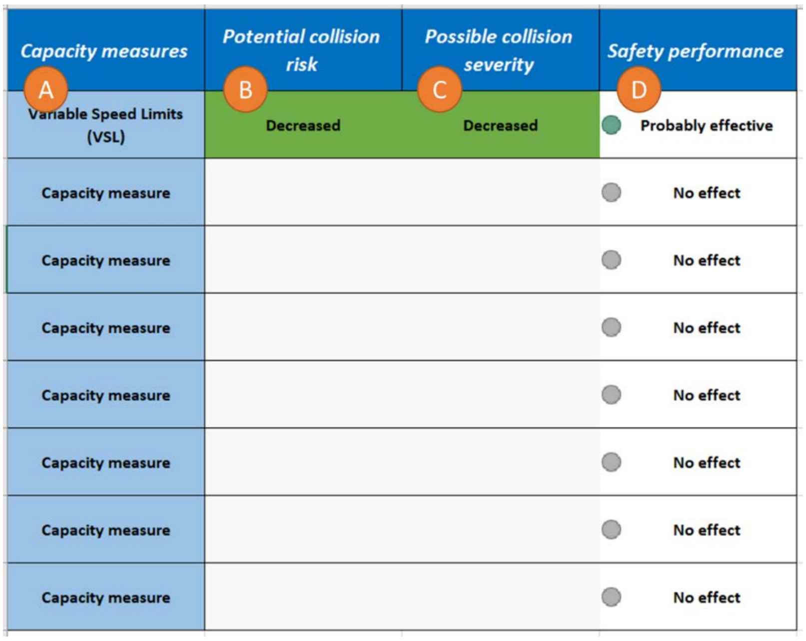


Figure 8: A screenshot from the ImpactOfCMsOnRiskFactors sheet of SAFEPATH-IIT

The *SafetyImpactResults* sheet of the tool provides the resulting safety impact indicators to the user (Figure 9). This contains the following elements:

A. The capacity measure selection from the *UserInput* sheet
B. The impact on collision risk is computed according to the model described in Section 7. The capacity measure's impact on collision risk can be *decreased, increased, unclear*, or *no effect*. *Unclear* indicates that the capacity measure has both negative and positive impacts on the safety risk factors that affect collision risk and further analysis is needed. *No effect* indicates that the capacity measure does not have impact on risk factors related to collision risk.
C. The impact on collision severity computed according to the model described in Section 7. The impact on collision severity can be *decreased, increased, unclear*, or *no effect*. *Unclear* indicates that the capacity measure has both negative and positive impacts on the risk factors that affect collision severity and further analysis is needed. *No effect* indicates that the capacity measure does not have impact on risk factors related to collision severity.
D. Safety performance indicator values. These values can be *Probably effective, Probably ineffective, unclear*, or *no effect*.



Capacity measures	Potential collision risk	Possible collision severity	Safety performance
Variable Speed Limits (VSL)	Decreased	Decreased	Probably effective
Capacity measure			No effect
Capacity measure			No effect
Capacity measure			No effect
Capacity measure			No effect
Capacity measure			No effect
Capacity measure			No effect
Capacity measure			No effect

Figure 9: SafetyImpactResults sheet of SAFEPATH-IIT

The decision mechanisms used for the computation of the collision risk, collision severity and safety performance indicative values are explained in Appendix A.

8.2 How to use SAFEPATH-IIT

Figure 10 shows how to use the tool:

A. The user first selects a capacity measure that will be analysed.
B. The tool displays how the selected measure affects different risk factors. The user can examine the impact of the capacity measure on risk factors.
C. Using the input values of how the capacity measure affects the risk factors, the tool computes the indicative values for collision risk and collision severity.
D. Finally. the tool outputs the results in the results page.

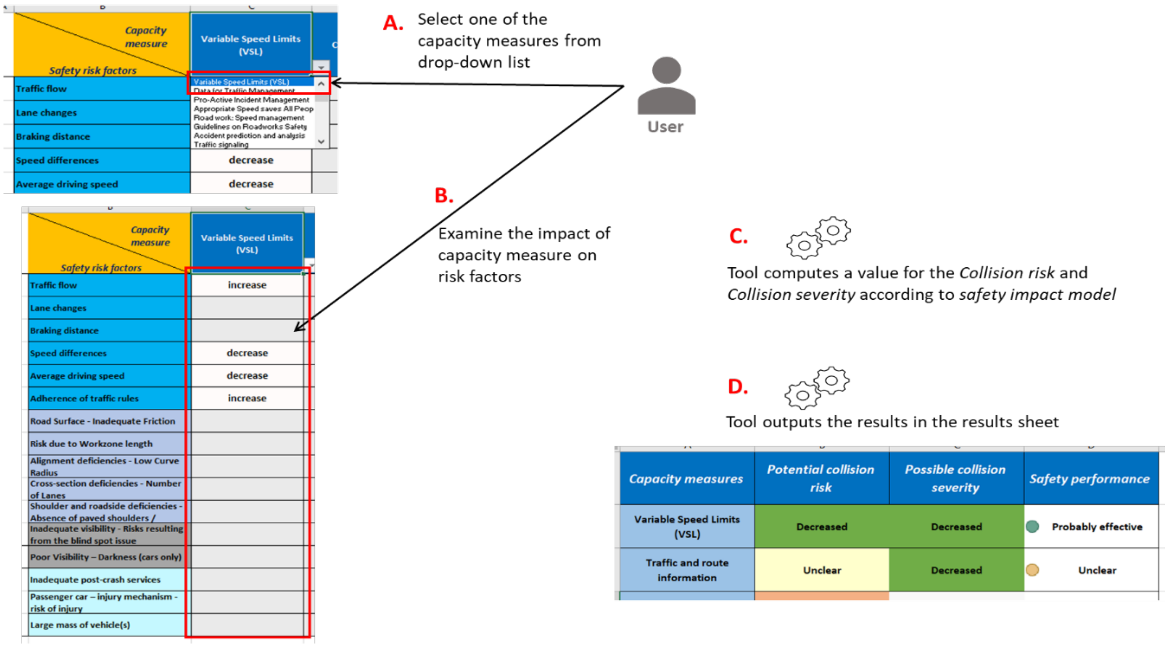


Figure 10: Illustration of the tool usage

An example usage of the tool can be found in Appendix B.

Tool usage tutorial:

1. The user opens the file SAFEPATH-IIT Excel file.
2. The user navigates to the first sheet named as *UserInput*.
3. The user will be presented with the user input page.
4. The user selects a capacity measure by clicking on the “Capacity measures” cell (*Step A*). A drop-down list of capacity measures appears. The user selects one of the capacity measures from the list.
5. The impact values of the capacity measure on the safety risk factors are presented to the user (*Step B*).
6. The user can repeat the steps 4 and 5 for different capacity measures by selecting different capacity measures – up to 8 capacity measures.
7. The tool automatically computes an indicator value for each capacity measure and shows the results in the *SafetyImpactResults* sheet (*Step C*).
8. The user can navigate to the *SafetyImpactResults* sheet and examine the results (*Step D*).

9 Impact of future developments on the safety of capacity measures

This section discusses the readiness of some of the measures in SAFEPATH countries.

9.1 General readiness of SAFEPATH countries

NRAs are already working on digitalisation and connectivity as enablers for improved services of the future. Digitalisation technology includes **ITS measures such as variable speed limits, variable message signs, and managed lanes** to improve safety and capacity on highways. In Europe, the main areas of application of managed lanes are Western Europe and metropolitan areas, as shown in *Figure 11*.

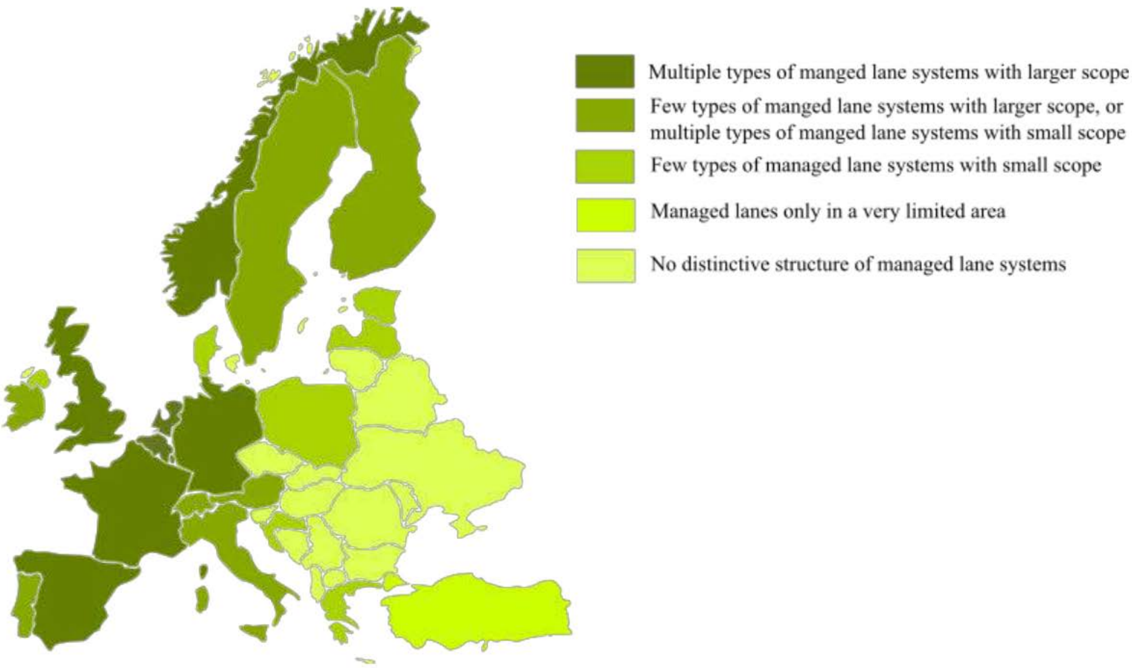


Figure 11: Degree of managed lanes application in Europe (own findings based on private communication) [21].

One of the most effective traffic management measures – managed lanes – encompasses a range of traffic engineering measures, including HOV lanes, special use lanes, hard shoulder usage, and dynamic control signs. Many transport authorities have recognised the potential of managed lane systems. A recent study [21] analysed the operation of managed lanes in Europe. It provided a comprehensive overview of hard shoulder usage, high occupancy vehicle lanes (HOV lanes), and dynamic message signs (DMS) by surveying the transport and traffic ministries in Europe. Table 10 provides an overview of their findings in the SAFEPATH countries.

Table 10: Managed Lanes overview in SAFEPATH countries

Countries	Traffic management measures (Dynamic message signs, HOV, and hard shoulder running)
Austria	On the A7 highway, there is currently an 8 km bus lane to accelerate public transport. The use of HOV lanes on motorways is being intensively tested. The use of section control to monitor speed is noteworthy.
Belgium (Wallonia)	17km HOV lane exists on motorways. Lengths of the special lanes are not recorded.
Germany	Temporary hard shoulder use is currently being used on 414 km. Reversible lanes are increasingly tested in construction zones, but not used on the open road. Various measures are being investigated for automating traffic seen as high potential in future.
Ireland	On some stretches, certain lanes are closed to heavy traffic to improve traffic flow. Beyond that, there are no other traffic control measures.
Hungary	Hungary does not use managed lane systems on its highways.
Netherlands	Around 161 km of temporary lanes are in place for peak hours during rush hour. Around 48 km of interlinking lanes are used to harmonise traffic. Around bigger cities like Amsterdam or Rotterdam, ramp metering is used to harmonise traffic flow on highways. Resumption of HOV lanes is under discussion.
Finland	Does not currently use managed lane systems on its highways. The focus is on the automation and digitalisation of traffic.
Sweden	There are several innovative approaches to optimise traffic flows, capacity utilisation, and emissions.
UK	Various active traffic management features are applied on several motorways such as managed motorway measures.

The way countries apply TIM varies significantly in their organisation, responsibility, and specific measures. Research and development efforts in Europe are very fragmented. Initiatives such as CEDR and EasyWay align the individual TIM activities. Some member states did not participate in the CEDR survey [23]. Moreover, countries have different TIM priorities dictated by geography, climate, and driver culture. The exact comparison of TIM between SAFEPATH countries will be highlighted in the final report.

9.1.1 Intelligent Transport Systems (ITS)

Digitalisation includes Intelligent Transport Systems (ITS) measures **such** as variable speed limits, variable message signs, and managed lanes to improve safety and capacity on highways. The levels range from Level 0 to Level 4 (*Table 11*) and are based on the EasyWay Incident Warning and Handling Deployment Guidelines [87].

Table 11: ITS levels description (Source: TEN-T 2019 performance report)

Level 0	None
Level 1	Monitoring system (e.g., real-time data about traffic/weather conditions is collected by the road administration)
Level 2	Traffic information system (road administration passively manages the network e.g., information about traffic/weather conditions is provided to road users)
Level 3	Traffic management system (road administration actively manages the network e.g., variable speed limits, dynamic lane management, ramp metering)
Level 4	Cooperative ITS (i.e., vehicle-to-vehicle or infrastructure-to-vehicle information)

The levels vary between countries, with different countries are at different stages of deployment and implementation. Trans-European Road Network performance report from 2019 [81] published the maturity level of ITS on TEN-T road network, out which we present the data for SAFEPATH countries in *Table 12*.

Table 12: Distribution of ITS by level in SAFEPATH countries, as supplied by these countries

Country	Total length (km)	Level 0	Level 1	Level 2	Level 3	Level 4
Austria	1740		83.60%	0.00%	15.00%	1.40%
Belgium (Flanders)	948		0.00%	34.30%	65.70%	
Finland	5205		0.00%	82.90%	17.10%	
Germany	10713		0.00%	49.50%	50.50%	
Hungary	1474	3.50%	6.30%	69.20%	11.30%	9.80%
Ireland	2163	84.30%	7.50%	8.10%		
Netherlands	1886		7.70%	6.60%	85.60%	
Sweden	6417			92.40%	7.60%	
United Kingdom	4441	0.10%		51.30%	48.60%	

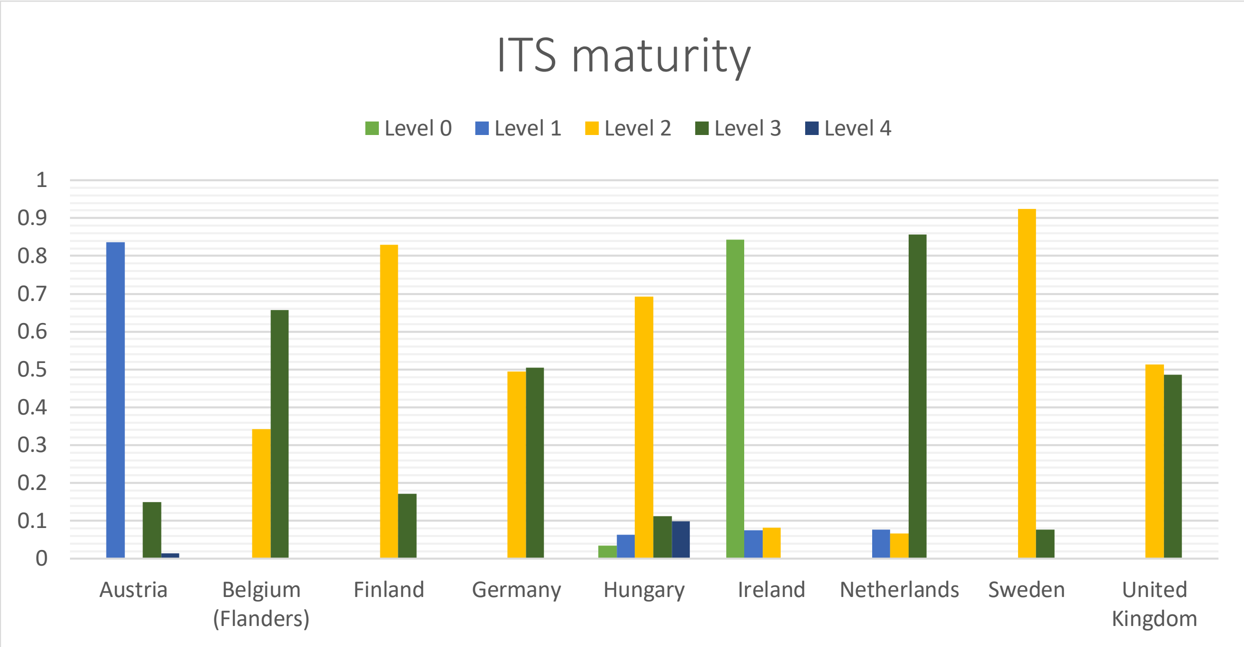


Figure 12: ITS maturity among SAFEPATH countries

It is clear from Figure 12 that countries such as the Netherlands, Belgium, Germany and the UK are engaged in enabling level 3 ITS. The majority of SAFEPATH countries are engaged in enabling level 2 ITS. Belgium (Wallonia) did not participate, and hence there is no information on where it stands in ITS maturity level. The statistics data is from 2019, and there is a high probability that some of these countries will have progressed in enabling ITS since then.

9.1.2 Cooperative intelligent transport systems (C-ITS)

Cooperative ITS (C-ITS) are a further step in the logical evolution of ITS development, ensuring that information – especially when it is safety relevant – is available when needed. To make the most of the opportunities available from C-ITS, it needs the cooperation and coordination of NRA to successfully establish a European roll-out (a joint effort from the public and private sector). NRAs need to focus on developing ever more automated processes for managing traffic, objects, and incidents.

CEDR’s Connected Automated Driving working group – as part of the European umbrella organisation of NRAs – addresses this challenge by taking stock of individual NRAs’ expectations for infrastructure changes needed in the next decade [82]. They will explore the likely impact of connected and automated driving on road authorities and discuss the disruptive changes that will significantly alter the NRAs roles and responsibilities.

With C-ITS Day 1, 1.5 and 2 services being rolled-out where applicable (for instance road works warning and In-vehicle speed limits; it was agreed by the EC C-ITS Platform that these services are expected to and should be available in the short term because of their expected societal benefits and the maturity of technology, although are being delayed by lack of in vehicle fitment). Therefore, the evidence of safety impact of the C-ITS services is limited but will improve in coming years. An example is Nordic Way, which involves pilot C-ITS deployment in Finland, Sweden, Norway, and Denmark.

9.2 New developments likely to impact the road safety of capacity measures

Some developments that are likely to have impact on road safety of capacity measures are listed in *Table 13*. We investigated these developments in vehicles (e.g., CAV, ADAS, V2X, C-ITS) that are likely to impact on road safety of capacity measures in Phase 2. The sections below provide information on these developments, many of which are now mandatory in new vehicles since July 2022.

Table 13: Some advanced developments that are likely to have impact on road safety of capacity measures

Advanced development	Description
Lane keeping assist	The lane keeping system aim to decrease the amount of unwanted lane departures by determining the dangerous situations and intervenes only in instance where the driver mismanages steering control by issuing warning/intervention strategies [46].
Automatic emergency braking	The automatic emergency braking (AEB) system is an active safety system for avoiding rear-end and pedestrian collisions. This system is an advanced assistance system designed to identify imminent collisions and react by automatically activating the brakes and is based on camera recognition of an object in front of the vehicle [47].
Adaptive cruise control	An ACC system allows drivers to maintain a desired cruise speed if there is no preceding vehicle as well as a desired following gap with respect to a preceding vehicle [48]. There are concerns about its early performance emerging and so the current performance is inconclusive.
Blind spot detection	Blind Spot Detection systems assist in avoiding collisions by providing warning messages. Blind Spot Detection systems have the capacity to save up to 66 lives and around 10000 injuries in Europe yearly by 2030 at full system penetration [49].
Vehicle to vehicle communication	Using radio communication, vehicle positions are communicated to neighbouring vehicles to reduce collision risk.

9.2.1 Lane Keeping Assist

The lane keeping system aims to reduce the amount of unwanted lane departure by detecting dangerous situations and intervenes only in instance where the driver mismanages steering control by issuing warning/intervention strategies [46].

The available literature mostly focused on Lane Departure Warning (LDW) systems, while there are very few studies on the effect of Lane Keeping Assistants (LKA). The literature mostly describes the benefit of LDW systems by identifying the target population [52]. Little is known however about the number of cases where LDW would have been effective. LDW alone will not be able to restore the attention of a driver that has fallen asleep in time to avoid an unintentional lane departure but will be helpful in cases of brief lapses of attention, for example in operating touch-screen infotainment systems.

9.2.2 Automatic emergency braking

Automatic emergency braking (AEB) system is an active safety system to help avoid rear-end and pedestrian collisions. This system is an advanced assistance system designed to identify imminent collisions and react by automatically activating the brakes. It is based on camera recognition of an object in front of the vehicle [47], [52]. The term AEB is usually followed either by the words “city” or “interurban” which designate the environment where it is designed to be the most efficient. AEB city is effective only at low speeds (below 30 or 50 km/h) while AEB interurban is effective only at high speeds.

The review of the effectiveness of AEB suggests that this is an effective measure [52]. While no studies were found dealing with AEB interurban, the studies dealing with AEB city suggest that it has a positive effect on road safety.

9.2.3 Adaptive cruise control

An Adaptive Cruise Control (ACC) system allows drivers to maintain a desired cruise speed if there is no preceding vehicle as well as a desired following gap with respect to a preceding vehicle [48].

Existing studies in the literature indicate that ACC affects road safety through monitoring and maintaining a safe following distance to a vehicle ahead [52]. The outcomes of this measure are normally recorded in terms of driver comfort or stress, or as an impact on the traffic flow and performance. Time headway and following distance are major factors for both the overall traffic flow performance and safety outcomes of a particular road segment. Short following distances and time gaps to vehicles ahead affect safety, as there may not be sufficient time to stop or avoid another vehicle in the case of an emergency. ACC systems help to prevent short following distances by monitoring and maintaining a safe following distance to a vehicle ahead by automatically adjusting vehicle speed. This is particularly helpful in stable driving conditions, such as motorways and other high-speed roads where a vehicle can follow another vehicle for sometimes extended periods. There is, however, insufficient information for its effectiveness, and many emerging concerns about its ability to read road signs consistently and safely, meaning drivers may choose to disable it

9.2.4 Blind spot detection

Blind Spot Detection systems assist in avoiding collisions by providing warning messages. A study [49] estimated that Blind Spot Detection systems have the capacity to save up to 66 lives and around 10000 injuries in Europe yearly by 2030.

The blind spots – areas in angles of view which are out of line-of-sight of the driver – of passenger cars and heavy goods vehicles are different. Blind spot detection for passenger cars is a driver assistance system that supports the driver in lane changing if they carry out an inadequate glance over the shoulder or fail to look at all. The blind spot of an HGV is a major problem [52], because the limitation of visibility due to vehicle structure is larger, meaning areas around the driver's cabin are completely obstructed. These limitations can be overcome with the aid of mirrors, camera-monitor systems, new window designs and other measures. A driver assistance system such the one for cars that recognises vehicles in the parallel lane, can prevent accidents on motorways or during overtaking.

In the literature it is estimated that assistance systems for blind spot detection would probably be effective in most of the blind spot scenarios. There are many papers about the improvement of the direct vision of HGV drivers, regardless of the system, but none of them can provide statistically worked out data showing a safety benefit. They claim the effectiveness of systems by showing the improved vision from the driver's cabin or the implementation of an additional system without influencing the existing structures and visibility. So, these systems are probably effective, but there are no studies that provide data from real life [52].

9.2.5 Vehicle to vehicle communication

Vehicle to Vehicle communication has the potential to reduce collisions by alerting vehicles that are approaching surrounding vehicles on collision paths [52]. The technology is not yet operational in traffic and quantitative analyses are not yet available.

Using radio communication, vehicle positions are communicated to neighbouring vehicles to reduce collision risk. This feature is not limited to line-of-sight conditions and thus can be effective in more scenarios than existing collision avoidance systems. There are no quantitative results for the safety performance of vehicle-to-vehicle systems as they are not commercially viable, but preliminary analyses indicate positive effects for safety.

9.3 Impact of future developments on road safety

Digital technologies - artificial intelligence (AI), machine-learning, image processing, internet-of-things (IoT), smartphone applications, geographic information system, global positioning system, drones, social media, virtual-reality, simulator, radar, sensor, big data all provide useful means for identifying and providing information on road safety factors including road user behaviour, road characteristics and operational environment [69]. Moreover, the results in the literature show that digital technologies such as AI, Image processing and IoT have been widely applied to enhance road safety, due to their ability to automatically capture and analyse data while reducing the possibility of human error. However, a key gap in the literature remains on evaluating their effectiveness in real-world environments. This limits their potential to be utilised by policymakers and practitioners.

The same study identifies one significant gap in the current literature on the applicability of digital technologies for road safety, namely that there is still limited understanding of how these technologies work in practice and of the benefits gained. A limited number of studies investigated the effectiveness or quantified the impacts of such technologies in real life. While emerging and advanced digital technologies have the potential to improve road safety, well-designed studies with sufficient evidence in their adoption is needed. More studies are therefore needed to build confidence that investing in these systems will reap the intended rewards and are worth the investment.

9.4 Transferability of capacity measures outside SAFEPATH countries

It must be kept in mind that the European highway and expressways network cannot be compared with that in countries such as the USA. The countries in Europe are generally much smaller than American states, and driven distances are often significantly shorter. Measures that might be appropriate for the USA may not yield the same benefits in the EU. The same logic applies to more extensive and smaller developed and developing countries for transferring the measures.

Thus, rather than directly applying the measures from developed countries, it is worth analysing the risk and cost of the measures. This can be done using a ‘benchmarking’ approach such as that developed by “*SUNflower: a comparative study of the developments of road safety in Sweden, the United Kingdom, and the Netherlands*” [31]. These three countries are considered best in the world in terms of road safety. A report from 2016, “Road accidents in Finland and Sweden: A comparison of associated factors”, is an example of comparing the road safety aspects of Finland with Sweden [32].

10 *Speed management*

In this section we share the findings on speed management in accordance with the request for speed management for work zone in the DoRN document.

Speeding is defined as exceeding the posted speed limits or driving too fast for conditions [1][2]. Speeding is the most critical road safety problem in many countries, contributing to one-third of fatal collisions, and an aggravating factor in the severity of all collisions [6]. Drivers who maintain a speed higher than the average speed run a higher collision risk than drivers who maintain a speed equal to or lower than the expected average speed. Figure 13 shows the percentage of collisions due to speeding, and the factors that affect speeding – geographical location, road design, roadside characteristics, and driver's attributes.

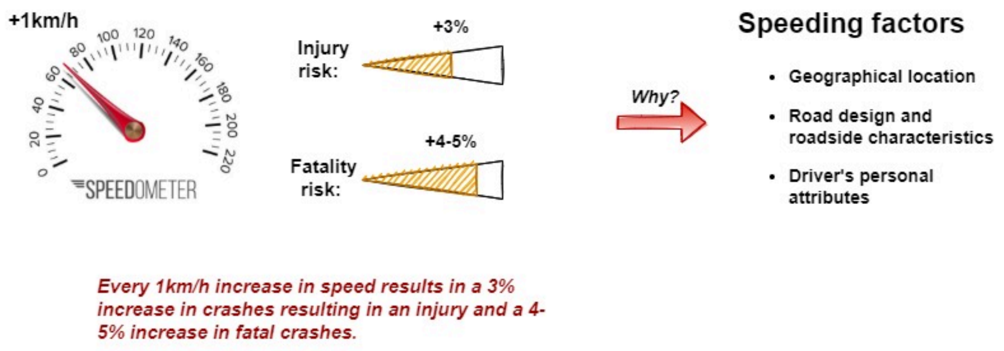


Figure 13: Global status report on road safety 2018 (World Health Organisation)

1. **Geographical location**

A recent analysis by Zijun, L et al. [10] discusses many factors that affect driver's speeding. The geographical location of drivers accounted for about 7.7% of the variability in the likelihood of a driver driving over the posted speed [10]. For example, drivers feel confident about speeding on long and straight-line roads, leading to less vigilance and more speeding.

2. **Road design and roadside characteristics**

a) Road design

European countries have developed road design speed guidelines independently of each other. However, they are similar in design principles. The distinguishing characteristics are highlighted in reports such as AASHTO [38]; DHV [83]; FGSV [84]. For example, a design speed of 120Km/h is normally used in the Netherlands for Type I motorways (DHV, 2005). In contrast, the recommended speed for mountainous terrain is 80-100km/h. However, along with speed guidelines, specific road design characteristics such as pavement conditions also play a crucial role in influencing road speed. For instance, poor pavement conditions will cause more critical vehicle movements at higher speeds [33].

b) Roadside characteristics

When a vehicle speed is high, collisions that involve running into roadside hazards will be more severe. In 80 km/h speed limits, 1 in 25 recorded **run-off-road casualty collisions** will be fatal. In 110 km/h speed limits, 1 in 15 will result in a fatality [34].

3. **Driver's personal attributes**
Speeding is a common driver misbehaviour and one of the major causes of traffic collisions [10][12]. Many drivers are subject to a 'time saving bias', tending to drive at a higher speed [14]. Attitude is the key deciding factor in a driver's speeding behaviour. The effects of age and personality are also significant [10]. The reasons for exceeding speed limits can be time pressure, enjoyment, or carelessness resulting in failure to notice the posted limit or their own speed.

Speed management comprises a set of measures that help mitigate the adverse effects of excessive and inappropriate speed on roads. We classify the measures that mitigate speeding on highways into physical and digital measures. However, here we focus only on the few critical measures to be described in this report. We also highlight speeding measures specific to work zone areas.

1) Physical measures - Road markings
2) Technological (Digital) measures – Speed Camera (speed enforcement) and Variable Speed Limits (VSL)
3) Speed management in work zones

10.1 Physical measures – road markings

Physical measures include road typology, geometric road design, pavement characteristics, road markings and similar factors. [9].

Out of many, we explain road markings' benefits in mitigating highway collisions by influencing the driver's speeding behaviour. The potential for using road markings to indicate speed limits by painting them on the road was investigated in a controlled experiment published in "*Using road markings as a continuous cue for speed choice*" [15]. The findings indicate that providing continuous speed limit information to drivers would improve safety by increasing the drivers' uniformity of driving speeds. Further studies [15] [16] [17] indicated the usefulness of road markings for reducing the speed in advance of dangerous bends or gradients. The findings showed a reduction in collisions severity, especially in the mountainous sections.

10.2 Digital measures – digital information for drivers and vehicles

The term *digital measure* refers to the availability of information for drivers and vehicles – e.g., HD maps and weather and traffic conditions, and the physical facilities, such as variable speed signs, necessary for driver compliance. Out of those, we shall highlight speed cameras and variable speed limits.

10.3 Speed management in work zones

CEDR, in the call for the 2012 programme [35], set the vision of zero road worker injuries or fatalities. This is consistent with many of the major pan-European companies who work in road construction and maintenance, who each have their own vision for zero accidents.

Speed management in work zones is important for the safety of both the road user and the road worker.

There are two projects covered by the 2012 Research Call on Safety at Work zones:

- ASAP - Appropriate Speed saves All People - which focuses on recommending the best methods of controlling speeding through roadwork zones. The ASAP guidelines can be used for choosing

[9] SMART ROADS CLASSIFICATION A PIARC SPECIAL PROJECT, 2021

the best methods to achieve appropriate speed behaviour in work zones. A description of each measure and its advantages, application fields, expected impact, on-site deployment issues and cost components can be found on http://asap.fehrl.org/.

- BRoWSER - Baselining Roadworks Safety on European Roads - which considers two aspects, improving data collection on worker injuries and near misses, and understanding the optimum roadworks layouts that enable road users to approach, travel through and exit works without causing injury to workers and others. The full analysis can be found in the project deliverables on the project website http://browser.zag.si [85].

ASAP highlights the limitations in the measures' effectiveness if performed in isolation. It is more effective to combine measures. For example, installing speed cameras may not yield effective changes in driver behaviour in reducing speed, but if combined with a driver speed monitoring display or VMS it can influence the behaviour. ASAP recommends considering three road work locations accompanied by a combination of specific measures to keep the work zone area safer – the advanced warning area, transition area, and the actual work zone, briefly described in Table 14.

Table 14: Recommended measures - Motorway, long-term, and short-term

(Source: ASAP, http://asap.fehrl.org/)

Advance warning area	Temporary static speed limit reduction
	Variable message signs
	Speed camera signs
Transition area	Temporary static speed limit reduction
	Driver speed monitoring display
	Police presence
Work zone area	Variable message signs
	Speed camera with worker warning

11 Conclusion

This report summarises the work which has been carried out in road safety analysis. The two outputs of the road safety analysis (WP4000) are a safety analysis of the selected measures which have the most comprehensive evidence of impact on capacity, and a system model for safety analysis to estimate the safety impact of capacity measures.

The safety performance within the SAFEPATH project is defined as the collision risk and severity of the collisions that impact the highway capacity. Thus, we first focused on the safety indicators, safety factors and KPIs that are critical on highway capacity. Then, we investigated existing methods on safety analysis for highways and summarised the identified methods for different categories as well as the scope of these methods.

By analysing the current state of knowledge and consolidating them from various credible sources such as CEDR, ESTC, AASHTO reports, and relevant scientific papers, we determined the *safety levels* for a set of selected capacity measures that align with WP3000. The selected measures and overview of the determined safety performances are shown in Table 15. The selected measures' benefits, limitations, and gaps are captured from the literature review mainly focusing on pre-post analysis studies and survey results or reports from NRAs.

Table 15: Overview of selected capacity measures' impact on safety

Category	Selected Capacity measures	Safety performance
Infrastructure	Hard shoulder running	Probably effective
	High occupancy vehicle lane	Probably effective
	Mandatory variable speed limit	Effective
	Ramp metering	Unclear result
	Intelligent traffic control system	Probably effective
	Tidal flow operation	Unclear result
	Lane redesign and adjustments	Unclear result
	Traffic and route information	Probably effective
	Fog warning system	Probably effective
Road user behaviour	Speed enforcement using speed cameras	Effective
	Driver training and education	Probably effective
	Dynamic speed display signs	Effective
Vehicle technology	Intelligent speed adaptation	Probably effective
	HGV platooning	Unclear result
	Green light optimised speed advisory	Probably effective
Incident response	Faster response to incidents	Effective
	Access to emergency services	Effective
	Incident detection	Effective
	Institution cooperation	Effective
Regulations	Congestion pricing scheme	Probably effective
	Overtaking ban on HGVs	Effective

A safety impact analysis model has been developed which reveals the factors affecting system safety, as well as underlying interactions. The model predicts whether the safety impact of a capacity measure will be positive or negative. The model also provides a scientific understanding of the influencing risk factors, capacity measures, and criteria for assessing highway capacity and traffic safety.

NRAs will be able to use the model to identify the most salient safety factors in their highway networks. This can help in the decision-making process when implementing a capacity-enhancing measure.

A tool for estimating the safety impact of capacity measures has also been developed, complementing this report. The tool comes in the form of a Microsoft Excel spreadsheet, SAFEPATH-IIT.xlsx. It also contains the capacity measures with an overview of their impact on highway safety, and other factors.

We also highlighted the state of development of the capacity-enhancing measures in SAFEPATH countries, and commented on transferability between countries, and gaps in implementation. We presented *the extra measures taken or need to be taken to keep safety at the same level or even improve it*. For example, under speed management at work zone areas, studies suggest that integrating ITS measures such as variable message signs combined with speed cameras improves safety.

The report also highlights some critical knowledge gaps:

- Many countries do not have accurate information on collisions. Until such data is available, information about road design features and key safety behaviours in similar environments will have to be used to provide a means of identifying high risk locations and ways to address them. For a long-term benefit and assessing the capacity measures performance, data collection is vital importance, at least for high-risk routes (e.g., high volume roads) to allow measurement of safety problems and identification of measures.
- The Road Infrastructure Safety Management procedure is not fully implemented in most of the EU countries. The primary reason for not applying a RISM procedure is the lack of resources or tools. However, certain countries have already initiated addressing the RISM gaps. For instance, road safety training courses have been activated in the Netherlands and Belgium to effectively address the lack of staff knowledge to carry out tasks. The UK and Ireland have developed clear and comprehensive guidelines for conducting road safety audits and inspections.
- The reasons behind deploying speed cameras, and with that also the set-up and use of camera systems are different in different counties, making comparison difficult.
- Effective coordination and cooperation between emergency services establishes successful traffic incident management and hence restores capacity more rapidly. However, there are critical gaps and challenges encountered in this area. The main problems related to information sharing, communication, and coordination have been identified as the main bottlenecks for effective cooperation between emergency services. However, organisations are starting to realise that introducing new interoperable system concepts forms an important constraint for significantly improving cooperation. One of the interoperable solutions is to support information-sharing between public and private emergency services and road authorities.
- While emerging and advanced digital technologies such as AI, image processing, IoT, and embedded and virtual systems have been widely applied to enhance road safety, due to their ability to automatically capture and analyse data while reducing the possibility of human error [69], a key gap in the literature remains on evaluating their effectiveness in real-world

environments. To unlock their potential to be utilised by policymakers and practitioners, more well-designed studies are needed to quantify the impacts of such technologies in real life.

The next steps in the SAFEPATH project will be the creation of a Practitioners' Guide (WP5000). The results of the road safety analysis, along with results from the empirical research and the Practitioners' Guide, will be detailed in the final report, which will be worked on in WP6000.

The results of this project will be further taken to the dissemination process (WP7000) to spread the knowledge to relevant stakeholders. The project team plans to use a variety of means of dissemination such as online one-to-one sessions, workshops, webinars, social media posts, conferences and university lectures, to ensure the widest possible reach of the project results.

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Appendix A SAFEPATH-IIT safety performance decision mechanism

The following decision mechanisms are used for the computation of the *collision risk, collision severity* and *safety performance* indicative values:

Computation of a Capacity Measure's impact on Collision Risk (CR) and Collision Severity (CS)

{

Collision risk = no effect;

Collision severity = no effect;

No Of CR Increasing impacts = Count of *Increased* impacts on Collision Risk according to Table 9;

No Of CR Decreasing impacts = Count of *Decreased* impacts on Collision Risk according to Table 9;

No Of CS Increasing impacts = Count of *Increased* impacts on Collision Severity according to Table 9;

No Of CS Decreasing impacts = Count of *Decreased* impacts on Collision Severity according to Table 9;

If (**AND**(*No Of CR Increasing impacts*>0, *No Of CR Decreasing impacts*>0))

Collision risk = Unclear;

else if (*No Of CR Increasing impacts*>0)

Collision risk = Increased;

else if (*No Of CR Decreasing impacts*>0)

Collision risk = Decreased;

If (**AND**(*No Of CS Increasing impacts*>0, *No Of CS Decreasing impacts*>0))

Collision severity = Unclear;

else if (*No Of CS Increasing impacts*>0)

Collision severity = Increased;

else if (*No Of CS Decreasing impacts*>0)

Collision severity = Decreased;

}

Computation of a Capacity Measure's Safety Performance Indicator

{

Safety Performance= no effect;

If (**OR**(*Collision Risk ==* Unclear, *Collision Severity ==* Unclear*,* **AND**(*Collision Risk ==* Increased, *Collision Severity ==* Decreased)), **AND**(*Collision Risk ==* Decreased, *Collision Severity ==*Increased)))

Safety Performance = Unclear;

else if (**AND**(*Collision Risk == Decreased*, *Collision Severity ==* Decreased))

Safety Performance = Probably effective;

else if (**AND**(*Collision Risk ==* Increased, *Collision Severity ==* Increased))

Safety Performance = Probably ineffective;

}

Appendix B Example usage scenario for SAFEPATH-IIT

In Figure 14, user selects 8 different capacity measures. The impact of capacity measure on safety risk factors is automatically shown to the user. User can examine these values.

Safety risk factors \ Capacity measure	Variable Speed Limits (VSL)	Traffic and route information	Speed Cameras	Dynamic Speed Display Signs	Truck platooning	Green Light Optimized Speed Advisory (GLOSA)	Interchange Lane Control	Emergency cut through barrier
Traffic flow	increase	increase	increase	increase	increase	increase	increase	
Lane changes		increase			decrease		decrease	
Braking distance					decrease	decrease		
Speed differences	decrease		decrease	decrease	decrease	decrease		
Average driving speed	decrease		decrease			increase		
Adherence of traffic rules	increase		increase	increase	increase			
Road Surface - Inadequate Friction								
Risk due to Workzone length								
Alignment deficiencies - Low Curve Radius								
Cross-section deficiencies - Number of Lanes								
Shoulder and roadside deficiencies - Absence of paved shoulders /								
Inadequate visibility - Risks resulting from the blind spot issue							decrease	
Poor Visibility – Darkness (cars only)								
Inadequate post-crash services		decrease						decrease
Passenger car – injury mechanism - risk of injury								
Large mass of vehicle(s)					increase			

UserInput | SafetyImpactResults | ImpactOfCMsOnRiskFactors

Figure 14: Example - User inputs 8 different capacity measures

When user navigates to the *SafetyImpactResults* page (Figure 15), user can see the safety performance indicator values for each capacity measure. In the figure, we see that some safety performance indicator values are set as Unclear, which means that the capacity measure has both negative and positive impacts on the safety risk factors and further analysis is needed to obtain a more valid result.

Capacity measures	*Potential collision risk*	*Possible collision severity*	*Safety performance*
Variable Speed Limits (VSL)	Decreased	Decreased	Probably effective
Traffic and route information	Unclear	Decreased	Unclear
Speed Cameras	Decreased	Decreased	Probably effective
Dynamic Speed Display Signs	Decreased	Decreased	Probably effective
Truck platooning	Unclear	Unclear	Unclear
Green Light Optimized Speed Advisory (GLOSA)	Unclear	Unclear	Unclear
Interchange Lane Control	Decreased		Probably effective
Emergency cut through barrier	Decreased	Decreased	Probably effective

UserInput | SafetyImpactResults | ImpactOfCMsOnRiskFactors

Figure 15: Example – Safety performance indicators for the capacity measure selections in Figure 14

Appendix C Contributing project team members and experts

The various project team members and experts who have been involved in the process are mentioned in Table below.

Name	Organisation	Role
Anastasia Tsapi	Royal HaskoningDHV	Project team
Evert Klem	Royal HaskoningDHV	Expert
Jan van Liere	Royal HaskoningDHV	Expert
Marson Jesus	Royal HaskoningDHV	Project team
Peter Vlugt	Royal HaskoningDHV	Expert
Sacco Barendrecht	Royal HaskoningDHV	Project team
Shubham Bhusari	Royal HaskoningDHV	Project team
Shubham Soni	Royal HaskoningDHV	Project team
Ravi Chaudhary	Royal HaskoningDHV	Project team
Dave Cowell	AECOM	Project team
Edward Bingham	AECOM	Expert
Keith Gilmour	AECOM	Expert
Lee Street	AECOM	Expert
Jamie Uff	AECOM	Project team
Candida Spillard	AECOM	Project team
Scott Stephenson	AECOM	Project team
Stephen Heathcote	AECOM	Expert
Andy Graham	White Willow Consulting Ltd	Project team
Priyanka Karkhanis	Eindhoven University of Technology	Project team
Yanja Dajsuren	Eindhoven University of Technology	Project team
Gökhan Kahraman	Eindhoven University of Technology	Project team