



CAMBER

implementation and evaluation plan

Project deliverable D2.2

DELIVERABLE ADMINISTRATIVE INFORMATION

PROJECT ACRONYM	CAMBER
PROJECT START DATE	01/01/2025
PROJECT DURATION (MONTHS)	36
GRANT	101076963
CALL	HORIZON-CL5-2023-D6-01-10
TOPIC	<i>Better infrastructure safety on urban and secondary rural roads throughout a combination of adaptable monitoring and maintenance solutions.</i>
CONSORTIUM COORDINATOR	EIRA
TITLE OF THE DELIVERABLE	D2.2 – CAMBER implementation and evaluation plan
WORK PACKAGE	WP2 – Methodological and Technical Approach
TYPE OF DELIVERABLE	R — Document, report
DISSEMINATION LEVEL	PU - Public
STATUS – VERSION, DATE	Final – V1.0, 22/12/2025
SUBMISSION DATE	31/12/2025

AUTHORS/CONTRIBUTORS

Name	Organisation	Contribution
Reinier Jansen	SWOV	Editor, Executive summary; Sections 1,2,3,6; Annexes 1,2
Nathan Harpham	AGIL	Editor, Executive summary; Sections 3,4,5
James Bradford	IRAP	Editor, Section 5
Govert Schermers	SWOV	Editor, Sections 2,3,4,5; Annexes 1,2,4
Ksander de Winkel	SWOV	Sections 4,5; Annex 4
Diane Cleij	SWOV	Section 2
Heike Martensen	SWOV	Section 4
Angèle Picco	SWOV	Section 4
Drishti Khatri	AGIL	Section 4; Annex 4
Steve Lawson	IRAP	Annex 2
João Cardoso	LNEC	Sections 3,4,5; Annexes 1,2,3,4,5
Carlos Roque	LNEC	Sections 3,4,5; Annexes 1,2,3,4,5
Andreas Hula	AIT	Sections 4,5,6; Annexes 1,3
Isabela Erdelean	AIT	Sections 4,5,6
Peter Saleh	AIT	Sections 4,5,6; Annex 1
Paul Rosenkranz	AIT	Sections 4,5
Ángel Losada Arias	AIT	Sections 4,5
Sonia Zajac	AIT	Sections 4,5
Michael Aleksa	AIT	Sections 4; Annex 1
Ali Pirdavani	UH	Sections 4,5,6; Annexes 1,2
Mahdi Sadeqi Bajestani	UH	Sections 4,5,6; Annexes 1,2
Katia Paglé	ICCS	Sections 4,5,6; Annexes 3,5

Name	Organisation	Contribution
Anna Antonakopoulou	ICCS	Section 5; Annexes 3,5
Vangelis Tsougiannis	ICCS	Section 5; Annexes 3,5
Giannis Panagiotopoulos	ICCS	Section 5, Annexes 3,5
Itziar Urbieta	VIC	Annex 5
Matija Ezgeta	FPZ	Annex 3
Darko Babić	FPZ	Annex 5
Dario Babić	FPZ	Annex 5
Maja Sovina	FPZ	Annex 5
Monica Olyslagers	IRAP	Executive summary; Sections 1,2,4,5,6; Annexes 2

QUALITY CONTROL

	Name	Organisation	Date
Peer review	Ali Pirdavani	UH	08/12/2025
Peer review	Katia Paglé	ICCS	09/12/2025

VERSION HISTORY

Version	Date	Author
0.1	03/12/2025	All
0.2	17/12/2025	Editors
1.0	22/12/2025	Reinier Jansen

APPROVED FOR SUBMISSION BY

Name	Organisation	Approval date
Olivera Rozi	EIRA	23/12/2025

LEGAL DISCLAIMER

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101076963. UK participant iRAP is supported by UKRI grant number 10139277. UK participant Agilysis is supported by UKRI grant number 10157029. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. The information in this document is provided “as is”, and no guarantee or warranty is given that it is fit for any specific purpose. The CAMBER project Consortium members shall have no liability for damages of any kind including without limitation direct, special, indirect, or consequential damages that may result from the use of these materials subject to any liability which is mandatory due to applicable law.

Copyright © CAMBER, 2025.

TABLE OF CONTENTS

DELIVERABLE ADMINISTRATIVE INFORMATION	I
TABLE OF CONTENTS	V
LIST OF FIGURES	IX
LIST OF TABLES	IX
PROJECT EXECUTIVE SUMMARY	X
DELIVERABLE EXECUTIVE SUMMARY	XI
1 INTRODUCTION	1
1.1 STRUCTURE OF THE DOCUMENT	2
1.2 KEY ASSUMPTIONS	2
2 IDENTIFICATION OF CAMBER SOLUTIONS	3
2.1 CONCEPTUAL FOUNDATION OF THE STRATEGIC-TACTICAL-OPERATIONAL FRAMEWORK	4
2.1.1 <i>Origins and evidence underpinning the CAMBER framework</i>	4
2.1.2 <i>Adopting the framework in CAMBER</i>	5
2.2 METHODOLOGY FOR SOLUTIONS IDENTIFICATION	8
2.3 OVERVIEW OF CAMBER SOLUTIONS	8
2.3.1 <i>Summary of solutions</i>	8
2.3.1.1 Solution #1: Roadside cameras	9
2.3.1.2 Solution #2: Integrating and validating multiple data sources for correlation, reliability, and validity	9
2.3.1.3 Solution #3: Spatial specification	9
2.3.1.4 Solution #4: Data/metrics dictionary	10
2.3.1.5 Solution #5: Digital twins: Value and requirements	10
2.3.1.6 Solution #6: Organisational integration of road asset and road safety management	10
2.3.1.7 Solution #7: System Speed	10
2.3.1.8 Solution #8: Curve parameters	11
2.3.1.9 Solution #9: Interdisciplinary CBA – Framework for evaluating the integrated value of novel data sources	11
2.3.1.10 Solution #10: Work zones	11
2.3.1.11 Solution #11: Location-based probing – Mapping the spread of detected problems through targeted user probing	11
2.3.1.12 Solution #12: CCAM as mobile sensors	11
2.3.1.13 Solution #13: Crash-data informed RSM decisions	11
2.3.1.14 Solution #14: Safety measures during maintenance	12
2.3.1.15 Solution #15: Contract status	12
2.3.1.16 Solution #16: Crash prediction and risk modelling	12
2.3.2 <i>Mapping solutions to CAMBER components</i>	12
2.3.3 <i>Mapping solutions to system integration types</i>	14
3 IDENTIFICATION OF LOW-COST SAFETY INTERVENTIONS	16

3.1	DEVELOPING A ‘LONG-LIST’ OF LOW-COST INTERVENTIONS	16
3.1.1	<i>Organisation of the intervention long-list</i>	18
3.2	EVALUATION AND CO-CREATION	19
3.2.1	<i>Operationalisation of screening criteria</i>	19
3.2.1.1	Feasibility	20
3.2.1.2	Compatibility.....	20
3.2.1.3	Public acceptance	20
3.2.1.4	Benefit-cost ratio	21
3.2.2	<i>Operationalisation of performance evaluation criteria</i>	22
3.2.2.1	Crash and severity reduction.....	22
3.2.2.2	Cost-effectiveness.....	22
3.2.2.3	adverse effects on other road users	22
3.2.3	<i>Selection of interventions via co-creation</i>	23
3.2.4	<i>Review of selected pilot site interventions</i>	25
4	IMPACT ASSESSMENT	27
4.1	DEFINING THE SCOPE AND DESIRED OUTPUTS.....	27
4.2	METHODOLOGY REVIEW	30
4.3	THEORETICAL PRINCIPLES	32
4.3.1	<i>Cost-benefit analysis (CBA)</i>	32
4.3.1.1	Inputs for CBA.....	33
4.3.1.2	Performing CBA	34
4.3.2	<i>FSI estimation</i>	37
4.3.3	<i>Assumptions for CBA and FSI modelling</i>	39
4.4	EUROPEAN-WIDE IMPACT ESTIMATION	40
4.4.1	<i>Data requirements for Europe-wide extrapolation</i>	40
4.4.2	<i>Intervention uptake scenarios</i>	41
4.4.3	<i>Uncertainty and limitations</i>	42
5	EVALUATION FRAMEWORK	43
5.1	SCOPE OF EVALUATION FRAMEWORK	43
5.1.1	<i>Framework architecture</i>	43
5.1.2	<i>Pilot site testing</i>	46
5.2	COMPONENT 1: SAFETY-INTEGRATED MAINTENANCE SYSTEMS AND PROCESSES	48
5.2.1	<i>Purpose</i>	48
5.2.2	<i>Evaluation focus</i>	48
5.2.3	<i>Application of the evaluation framework</i>	49
5.2.3.1	Data dictionary	49
5.2.3.2	Testing procedures.....	49
5.2.3.3	Indicators.....	50
5.2.3.4	Weighted scoring.....	50
5.2.3.5	Outputs to impact assessment	50
5.3	COMPONENT 2: NEW-GENERATION DATA SOURCES.....	50
5.3.1	<i>Purpose</i>	50
5.3.2	<i>Evaluation focus</i>	51
5.3.3	<i>Application of the evaluation framework</i>	51

5.3.3.1	Data dictionary	51
5.3.3.2	Testing procedures.....	51
5.3.3.3	Indicators.....	52
5.3.3.4	Weighted scoring.....	52
5.3.3.5	Outputs to impact assessment	52
5.4	COMPONENT 3: DIGITAL TWINS	52
5.4.1	<i>Purpose</i>	53
5.4.2	<i>Evaluation focus</i>	53
5.4.3	<i>Application of the evaluation framework</i>	53
5.4.3.1	Data dictionary	54
5.4.3.2	Testing procedures.....	54
5.4.3.3	Indicators.....	55
5.4.3.4	Weighted scoring.....	55
5.4.3.5	Outputs to impact assessment	56
5.5	COMPONENT 4: ADAS PERFORMANCE.....	57
5.5.1	<i>Purpose</i>	57
5.5.2	<i>Evaluation focus</i>	57
5.5.3	<i>Application of the evaluation framework</i>	57
5.5.3.1	Data dictionary	57
5.5.3.2	Testing procedures.....	57
5.5.3.3	Indicators.....	58
5.5.3.4	Weighted scoring.....	58
5.5.3.5	Outputs to impact assessment	59
5.6	COMPONENT 5: LOW-COST SAFETY INTERVENTIONS	59
5.6.1	<i>Purpose</i>	59
5.6.2	<i>Evaluation focus</i>	59
5.6.3	<i>Application of the evaluation framework</i>	59
5.6.3.1	Data dictionary	60
5.6.3.2	Testing procedures.....	60
5.6.3.3	Indicators.....	60
5.6.3.4	Weighted scoring.....	61
5.6.3.5	Outputs to impact assessment	61
5.7	SUMMARY.....	62
5.7.1	<i>Key assumptions</i>	63
6	CONCLUSIONS AND IMPLICATIONS FOR CAMBER	64
6.1	DATA COLLECTION, FUSION AND PROVISION (WP3).....	66
6.2	SOLUTIONS INVESTIGATION AND DIGITAL TWINS (WP4)	67
6.3	PILOT TESTING AND EVALUATION (WP5).....	68
7	REFERENCES	70
ANNEXES	78	
ANNEX 1: CAMBER SOLUTIONS.....	78	
ANNEX 2: LOW-COST SAFETY INTERVENTIONS	99	
ANNEX 3: DATA DICTIONARY	158	
ANNEX 4: CBA METHODOLOGY REVIEW	166	

ANNEX 5: PILOT SITE APPLICATION PER COMPONENT 174

LIST OF FIGURES

Figure 1 — Hierarchical visualisation of strategic, tactical and operational management levels.	6
Figure 2 — Visualization of road management systems (left) and an example of their integration (right) at the tactical levels.	6
Figure 3 — Sense-plan-act paradigm applied to road management, involvement of CAMBER components 2-5.	7
Figure 4 — Number of solutions (total $N = 16$) involved in integration between road safety management (RSM) and road asset management (RAM) systems at three hierarchical levels (strategic, tactical, operational).	14
Figure 5 - Decision Tree for classifying impacts across the CAMBER components.	28
Figure 6 – Relation between four levels of the evaluation framework and tasks within WP5.	46

LIST OF TABLES

Table 1 — Overview of CAMBER solutions and their relation to project items and CAMBER components.	13
Table 2 — Overview of the number of interventions identified per source.	17
Table 3 — Interventions identified through co-creating in T4.1.	24
Table 4 — Preliminary plans for pilot site testing.	47
Table 5 — Overview of links between components, key KPIs, and monetizable benefits.	62
Table 6 — D2.2 contributions to project KPIs.	64

PROJECT EXECUTIVE SUMMARY

The Connected and Adaptive Maintenance for Safer Urban and Secondary Roads project ('CAMBER') aims to develop and demonstrate improved safety monitoring across urban and secondary rural road networks through real-time data feedback into road maintenance systems and proven low-cost interventions.

Performance metrics based on new-generation data sources will provide road managers up-to-date information on safety issues, damage, and routine maintenance and upgrade needs. Data collated from a range of sources, such as telematics, vehicle and smartphone sensors, and road user feedback, will feed into safety assessment models to flag what measures are required to ensure a safe road environment for all road users, including road-user minority groups with varying design needs, such as powered two-wheelers (PTW).

CAMBER will support this through much-needed research and testing of low-cost road safety interventions and low-impact maintenance techniques, including those for vehicles with advanced driver-assistance systems (ADAS). The approaches will be demonstrated on urban and secondary road networks in five European countries. CAMBER's economically-sound solutions and new knowledge will be communicated through established networks to European road managers, policymakers and industry to support the decision-making and investment needed for more efficient maintenance for safer urban and secondary roads.

Social Media:



@CAMBER-project



@CAMBERProject

For further information please visit CAMBER-project.eu

DELIVERABLE EXECUTIVE SUMMARY

The CAMBER project aims to improve the safety of urban and secondary roads through integrated, digitalised and cost-effective approaches to detect, diagnose and respond to maintenance and safety issues. A core part of this effort is the development and demonstration of 5 ‘CAMBER components’: new methods for integrating safety performance considerations into road asset management processes (component 1), making use of new-generation data sources (component 2), digital twins of the road environment (component 3), harnessing advanced driving assistance systems (ADAS) (component 4) and proven low-cost safety interventions (component 5). The principles and methodology for the evaluation and impact assessment of the CAMBER components are developed and refined in WP2 and will be tested and operationalised through simulations in WP4 and pilot demonstrations and impact evaluations in WP5. Deliverable D2.2 sets out the methodological, analytical, and operational foundations required to implement, evaluate, and assess CAMBER solutions selected by WP4 and WP5 across five pilot sites. It integrates the outputs of Tasks T2.3, T2.4, and T2.5, ensuring a consistent approach to solution selection, safety impact estimation and evaluation.¹

The deliverable presents:

1. **A structured catalogue of 16 CAMBER solutions** addressing CAMBER components 1-4, namely: new methods for integrating safety performance considerations into road asset management processes (component 1), making use of new-generation data sources (component 2), digital twins of the road environment (component 3), harnessing ADAS technologies (component 4). These solutions are linked to gaps identified in CAMBER deliverable D2.1 and are designed to support mainly tactical-level decision-making but also strategic and operational alignment, where possible.
2. **A systematic identification and assessment of low-cost safety interventions**, resulting in a shortlist of 30 context-appropriate treatments eligible for simulation and pilot deployment (CAMBER component 5). A transparent screening framework was applied, complemented by pilot-site co-creation activities to ensure operational feasibility and local relevance.
3. **A harmonised impact assessment approach**, based on recognised European methodologies (iRAP, SafetyCube, ERSO), adapted for CAMBER through the use of surrogate safety measures (SSM), Fatal and Serious Injury estimation (FSI), and context-sensitive cost-benefit analysis (CBA). Key methodological assumptions are stated explicitly, and limitations, such as variability in data availability and domain-specific evidence, are acknowledged.
4. **A comprehensive evaluation framework** that defines inputs, indicators, testing procedures, and scoring methods for all CAMBER components. This ensures consistency in data collection, validation, analysis, and reporting across laboratory and real-world environments.

¹ With deliverable D2.2, the CAMBER consortium finishes project milestone MS2: theoretical principles, methodological process and technical specifications for the development and testing of the CAMBER components.

The deliverable also discusses the main risks and constraints affecting system integration, including data compatibility, organisational readiness, and the feasibility of strategic-level alignment. These risks are accompanied by proposed mitigation measures and will be monitored throughout WP4 and WP5. Together, these elements provide a clear, scalable, and robust foundation for implementing CAMBER solutions at the pilot sites, and for assessing their potential European-wide impacts.

List of abbreviations and acronyms

Acronym	Meaning
AADT	Annual Average Daily Traffic
ABS	Anti-Lock Braking System
ADAS	Advanced Driver-Assistance Systems
ADF	Automated Driving Functions
AIT	Austrian Institute of Technology
API	Application Programming Interface
BCR	Benefit-Cost Ratio
CAMBER	Connected and Adaptive Maintenance for Safer Urban and Secondary Roads project
CAN	Controller Area Network
CBA	Cost-Benefit Analysis
CCAM	Cooperative, Connected and Automated Mobility
CEA	Cost-Effectiveness Analysis
C-ITS	Cooperative Intelligent Transport Systems
CSV	Comma-Separated Values
CVD	Connected Vehicle Data
DGT	Dirección General de Tráfico
DT	Digital Twin
ERSO	European Road Safety Observatory
EU	European Union
FESTA	Field opErational teSts support Action
FHWA	Federal Highway Administration
FSI	Fatal and Serious Injuries
FYRR	First Year Rate of Return

Acronym	Meaning
GDP	Gross Domestic Product
GIP	Graph Integration Platform
HD	High Definition
ICT	Information and Communications Technology
IM	Incident Management
IMU	Inertial Measurement Unit
iRAP	International Road Assessment Programme
IRI	International Roughness Index
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LiDAR	Light Detection and Ranging
LL	Living Lab
MAPE	Mean Absolute Percentage Error
ML	Machine Learning
NPV	Net Present Value
PDO	Property Damage Only
PET	Post-Encroachment Time
PIARC	World Road Association [Permanent International Association of Road Congresses]
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PTW	Powered Two-Wheelers
RA	Road Asset
RAM	Road Asset Management
RISM	Road Infrastructure Safety Management

Acronym	Meaning
RMSE	Root Mean Square Error
RNO	Road Network Operations
ROI	Return On Investment
ROMO	Road Monitoring
RS	Road Safety
RSM	Road Safety Management
RTM	Road Traffic Management
RSU	Roadside Unit
RT	Road Traffic
SafetyCube	Safety CaUsation, Benefits and Efficiency
SafetyCube DSS	European Road Safety Decision Support System
SDT	Signal Detection Theory
SPI	Safety Performance Indicator
SQL	Structured Query Language
SRIPs	Safer Roads Investment Plans
SSM	Surrogate Safety Measure
TTC	Time To Collision
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
VRU	Vulnerable Road User
VSI	Value of a Serious Injury
VSL	Value of Statistical Life
WP	Work Package
WTP	Willingness To Pay

1 Introduction

The CAMBER project aims to improve the safety of urban and secondary roads through integrated, digitalised and cost-effective approaches to detect, diagnose and respond to maintenance and safety issues. A core part of this effort is the development and demonstration of 5 ‘CAMBER components’: new methods for integrating safety performance considerations into road asset management processes (component 1), making use of new-generation data sources (component 2), digital twins of the road environment (component 3), harnessing ADAS technologies (component 4) and proven low-cost safety interventions (component 5). The principles and methodology for the evaluation and impact assessment of the CAMBER components are developed and refined in WP2 and will be tested and operationalised through simulations in WP4 and pilot demonstrations and impact evaluations in WP5.

This Deliverable, **D2.2**, provides the methodological foundation for those next stages of the project. It brings together three key elements from WP2:

- **The identification of CAMBER solutions to be considered for simulation in laboratory environments or real-world demonstration in the pilots**
This involves identifying the most relevant safety-integrated maintenance approaches, data sources, digital twin configurations, targeted ADAS systems and low-cost safety interventions for each pilot context. The identification process is grounded in criteria relating to feasibility, expected effectiveness, scalability, and alignment with CAMBER objectives, as outlined in Task 2.3. A subset of the identified solutions will be selected and evaluated in a laboratory setting (WP4). The outcome of this evaluation will inform which solutions will eventually be implemented in pilot site demonstrations (WP5).
- **The approach to impact assessment to be applied in WP4 and WP5**
This covers how safety and asset management improvements will be measured, including the use of surrogate safety indicators, behavioural and operational data, Star Ratings, and/or FSI estimation methods, and cost-benefit assessment (CBA). It also explains how pilot-level findings will feed into wider European-scale extrapolation.
- **The evaluation framework that will guide pilot implementation**
The framework sets out the procedures, metrics, and data requirements necessary to ensure that the digital twins and pilots generate meaningful, comparable and transferable insights. It has been designed with three main audiences in mind:
 - (1) *Project leadership* – to ensure the pilots collectively address the project objectives;
 - (2) *Pilot site leads* – to make clear what is expected in terms of consequences for implementation and data collection; and
 - (3) *Downstream work package leads* – particularly WP3, WP4 and WP5, who will rely on consistent outputs to support data collection, demonstration and impact assessment.

1.1 STRUCTURE OF THE DOCUMENT

The remainder of this document is organised into three main parts:

1. Selection of Solutions (Chapters 2 and 3)

Describes the canvassing and narrowing of candidate solutions and presents the selected solution set for pilot sites, based on criteria established in Task 2.3. Chapter 2 focuses primarily on non-intervention solutions (CAMBER components 1-4), whereas chapter 3 focuses exclusively on intervention solutions (CAMBER component 5).

2. Impact Assessment Methodology (Chapter 4)

Sets out the methods to be applied in WP5 to evaluate the safety, asset management and socio-economic impacts of the CAMBER solutions, including the cost-benefit analysis and broader impact modelling.

3. Evaluation Framework (Chapter 5)

Defines the procedures, indicators, and data requirements that structure pilot implementation, ensuring alignment with project objectives and comparability across sites.

Together, they ensure that CAMBER's demonstrations are robust, comparable across contexts, and capable of supporting the wider uptake of integrated, safety-informed maintenance approaches for urban and secondary road networks across Europe.

1.2 KEY ASSUMPTIONS

To ensure transparency, the core assumptions used in the remainder of the deliverable D2.2 are provided here:

- Pilot sites will provide the minimum required localised crash and exposure data for surrogate safety measures (SSM) and fatal and serious injury (FSI) estimation.
- Value-transfer methods and harmonised value of statistical life (VSL) and value of serious injury (VSI) will be applied where national estimates are unavailable.
- SSMs and iRAP FSI estimation models will be sufficient to estimate safety impacts within project timescales (since long before-after crash datasets are infeasible).

2 Identification of CAMBER solutions

To understand how road management systems can be better aligned and integrated, it is essential to view them through a common structural lens. The framework proposed in CAMBER builds on the well-established triad of strategic, tactical, and operational levels, which provides a logical hierarchy linking long-term vision to day-to-day actions. In the context of road asset management (RAM), road traffic management (RTM), and road safety management (RSM), the strategic, tactical, and operational levels represent three interconnected layers of decision-making that span from long-term direction to day-to-day delivery:

- The **strategic level** defines the overarching vision, policy objectives, investment priorities, and performance targets that guide how a road authority seeks to manage its network over years or decades.
- The **tactical level** translates these ambitions into programmes, plans, and resource allocations, determining what will be done, where, and with what methods based on risk, condition, user needs, and predicted outcomes.
- The **operational level** concerns the execution of these plans through day-to-day activities such as inspections, maintenance works, traffic operations, incident response, and monitoring.

When clearly aligned, the three levels provide a coherent and evidence-based way to translate high-level objectives into plans and to ensure that these plans are implemented, monitored, and reinforced through day-to-day operational actions.

By adopting this framework, CAMBER aims to bridge the conceptual and practical gaps that often exist between road asset management, network operations, and road safety management. Each discipline traditionally applies its own planning and decision-making processes, yet all share a similar need to move coherently from strategy to implementation. The three-tier structure thus provides a unifying perspective for integrating these domains, ensuring that interventions and data-driven management processes are coordinated, efficient, and mutually reinforcing.

This chapter has three main parts. Section 2.1 outlines how this strategic–tactical–operational hierarchy has been applied in related domains, its conceptual foundations, and its relevance to CAMBER’s integrated approach to infrastructure, mobility, and safety management. Section 2.2 describes the approach taken by the CAMBER team to identify potential solutions² for pilot site testing, which are then presented in Section 2.3.

² These solutions primarily focus on CAMBER components 1-4 (see below). Component 5 (i.e. low-cost safety interventions) will be the main focus of Chapter 3.

2.1 CONCEPTUAL FOUNDATION OF THE STRATEGIC-TACTICAL-OPERATIONAL FRAMEWORK

2.1.1 ORIGINS AND EVIDENCE UNDERPINNING THE CAMBER FRAMEWORK

The origin of the strategic-tactical-operational three-tier approach can be traced back to the military domain (Svechin, 1923), and was subsequently adopted and adapted in other fields, such as management theory (Anthony, 1965), in road design (Alexander & Lunenfeld, 1972), and in driving-behaviour modelling (Michon, 1985). It is also widely used in the transportation domain. For instance, in transport planning literature (Elbert et al., 2020; Neass, 2015; SteadieSeifi et al., 2014) and in road-asset management practice (FHWA, 2013; UKRLG, 2013; UNECE 2021; PIARC, 2019).

Within the scope of CAMBER, we focus on the impact of road management on infrastructure, mobility and road safety. In management terms, these fields are covered by Road Asset Management, Road Network Operations and Road Safety Management respectively (PIARC, 2023).

In **Road Asset Management (RAM)**, the three levels are well established and commonly referenced in RAM frameworks. Although descriptions of these levels vary slightly across sources (FHWA, 2013; UKRLG, 2013; UNECE, 2021; PIARC, 2019), their core distinctions are consistent. The strategic level involves defining the overarching vision, goals, and desired outcomes. At the tactical level, plans are developed to achieve these goals, incorporating risk analysis as well as performance prediction and evaluation. The operational level concerns maintenance operations and the collection of data.

For **Road Network Operations (RNO)**, this three-tier structure is less well established, but its terminology can still be found. In the PIARC RNO manual (PIARC, 2022), the strategic level is described as focusing on integrating the operations concept early in the development of all road infrastructure projects to maximise efficiency on existing and future road infrastructure. The tactical level then translates this strategy into improving operations, with the objective of reducing traffic delays and operating more efficiently on a day-to-day basis. While the operational level is not directly mentioned in this context, the manual does refer to operating levels where implementation of various services occurs, such as traffic management services, network control services, information services, planning and reporting services, and support services. These services, amongst others, collect and provide data, react to (planned) events, control and influence road users, and utilise performance monitoring.

Research papers on analytical tools that can be used within the RNO framework to inform decisions and optimise performance clearly refer to the three-tier structure. Neass (2015) argued that traffic forecasting should not use a “one-size-fits-all” modelling approach, but instead should differentiate between the strategic, tactical and operational levels. SteadieSeifi et al. (2014) explicitly structured their review of freight transport planning by strategic, tactical, and operational levels. Similarly, Elbert et al. (2020) focused on tactical network planning and design in multimodal transportation, highlighting the importance of the tactical layer as the link between strategic planning and operational control in network management.

For **road safety management (RSM)**, the strategic-tactical-operational three-tier structure is not fully applied (Jiao & Evdorides, 2024). Road safety management plans are instead more often built around the three-tier structure introduced by Bliss and Breen (2009). This structure can be viewed as three

inter-related elements: institutional management functions, interventions, and results. Institutional management functions are the functions that produce interventions to achieve the desired long and medium-term road safety results, expressed as a vision and related performance targets. The results refer to the desired outcomes of the interventions.

While not directly translatable to the strategic-tactical-operational three-tier structure, some similarities exist. Both the institutional management functions and the strategic level focus on setting long-term goals. What exactly needs to be done to achieve these goals, i.e. the interventions, is often shaped in detail at the tactical level. Finally, data collection occurs at the operational level and produces the results that ought to be compared to the desired results, as described by Bliss and Breen (2009). The main difference between these two hierarchical structures is that the strategic-tactical-operational framework primarily describes organizational levels of activity, i.e., groups of people operating at different time horizons, whereas the Bliss and Breen (2009) structure distinguished between fundamentally different system components: institutional management (governance and coordination), interventions (programs and procedures), and results (performance data and desired outcomes).

Nevertheless, the strategic-tactical-operational framework has previously been used in the field of Road Safety Management. It is, for example, used in a governance model proposed in projects of Austroads (DITRDCA, 2023; Austroads, 2023). Also, Godthelp et al. (2024) stated that the well-known Safe Systems approach conceptualizes the road safety problem as a multi-level phenomenon, requiring measures at strategic, tactical, and operational levels, and recommend implementing it accordingly.

At the strategic level, countries are encouraged to define their vision for road safety, establish overarching goals aligned with their safety culture and the Sustainable Development Goals, and build the institutional and knowledge infrastructure needed to translate these principles into practice. At the tactical level, this vision is operationalised through the development of frameworks, regulations, and system designs that guide how transport systems, road networks, and vehicle technologies should evolve to improve safety. At the operational level, asset owners and implementers apply these frameworks in practice by managing and adapting specific roads, vehicles, and operations, supported by effective enforcement and post-crash care systems.

2.1.2 ADOPTING THE FRAMEWORK IN CAMBER

The proposed strategic-tactical-operational framework is a suitable framework for CAMBER, where having a consistent structure for the five components will support the main goal of integrating these management systems for optimal efficiency and impact.

Based on the definitions from the literature highlighted above, the levels are described as follows:

- **The strategic level:** the definition of long-term vision and objectives,
- **The tactical level:** the development of interventions to achieve goals (including data logging, data analysis and intervention selection), and
- **The operational level:** the implementation of interventions and data gathering.

This structure is visualised in Figure 1. It highlights the interaction between the operational level and the input is real world data and the output is the intervention impact.

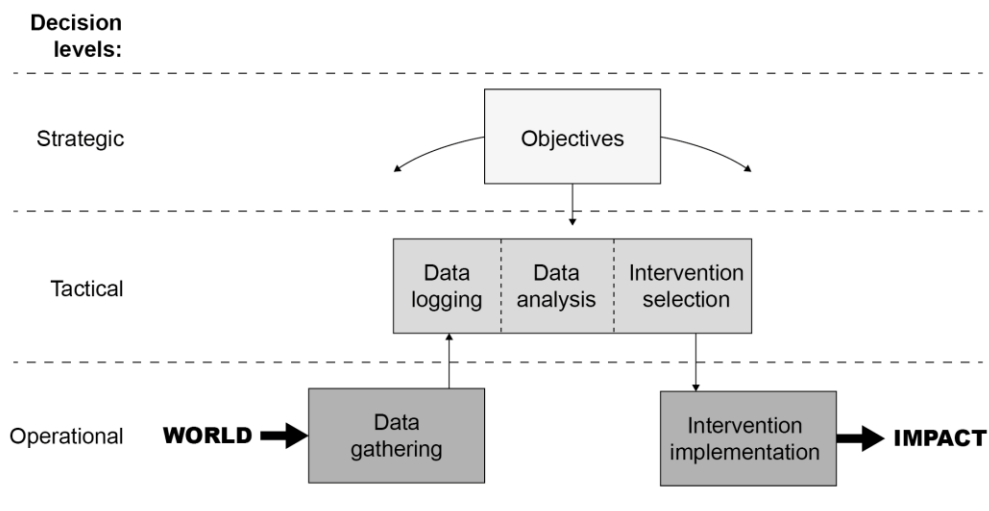


Figure 1 — Hierarchical visualisation of strategic, tactical and operational management levels.

Figure 2 If each road management system (RSM, RTM, RAM) can be described in terms of the strategic-tactical-operational framework, then integration of these systems could be described at these hierarchical levels, too. As shown in the left panel of Figure 2, each road management system features the blocks featured in Figure 1. An hypothetical example of integration specifically at the tactical level is shown in the right panel of Figure 2. Complete integration of all management systems can be defined as having interactions (arrows, or connections) between all levels of all systems. In this framework, CAMBER component 1 (safety integrated maintenance systems and processes) involves any integration involving at least RSM and RAM.

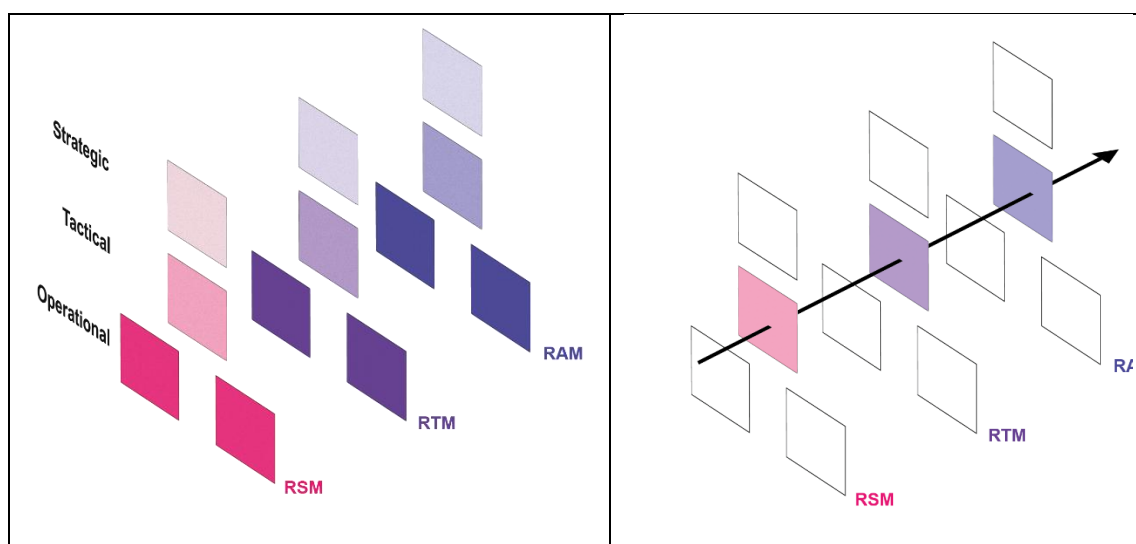


Figure 2 — Visualization of road management systems (left) and an example of their integration (right) at the tactical levels.

Another aspect to consider is feedback. Feedback is essential because it allows a system to learn from what is happening in the real world and continuously improve its decisions and actions. In road asset management and road safety management, feedback ensures that plans are not made in isolation: real-time and accumulated information about road conditions, user behaviour, traffic performance, crashes, near misses, and intervention outcomes is fed back into the management cycle. This enables authorities to detect emerging risks, verify whether interventions are having the intended effect, and adjust priorities or strategies when conditions change. Without feedback, management becomes static and reactive; with feedback, it becomes adaptive, evidence-based, and better able to achieve long-term safety and performance goals.

To clarify how road management processes create a continuous feedback loop with real-world conditions, it is helpful to interpret them through the lens of a sense–plan–act paradigm. A sense–plan–act paradigm is commonly used to describe systems across domains, such as robotics (Nilsson, 1984; Siegel, 2003), human behaviour (Miller, Galanter & Pribram, 1960), and management (Teece, 2007). Objectives are set for sensing (data gathering), planning (data logging, analysis, and intervention selection), and acting (intervention implementation) as visualised in Figure 3.

This feedback loop is addressed by CAMBER components 2-5, as shown in Figure 3. Component 2 (New-generation data sources) involves data gathering (e.g. through mobile apps) and logging, as well as validation of the data sources (i.e. analysis). Component 3 (Digital twins) concerns visualising logged data to facilitate analysis and potential intervention selection. Component 4 (ADAS performance) is similar to component 2 and involves data gathering and logging (including potential procurement), but the purpose of the analysis is to gain insight into relations between road quality and ADAS performance, instead of validation of the data sources. Component 5 (Low-cost safety interventions) concerns selection, verification, and implementation (e.g. pilot site testing) of interventions.

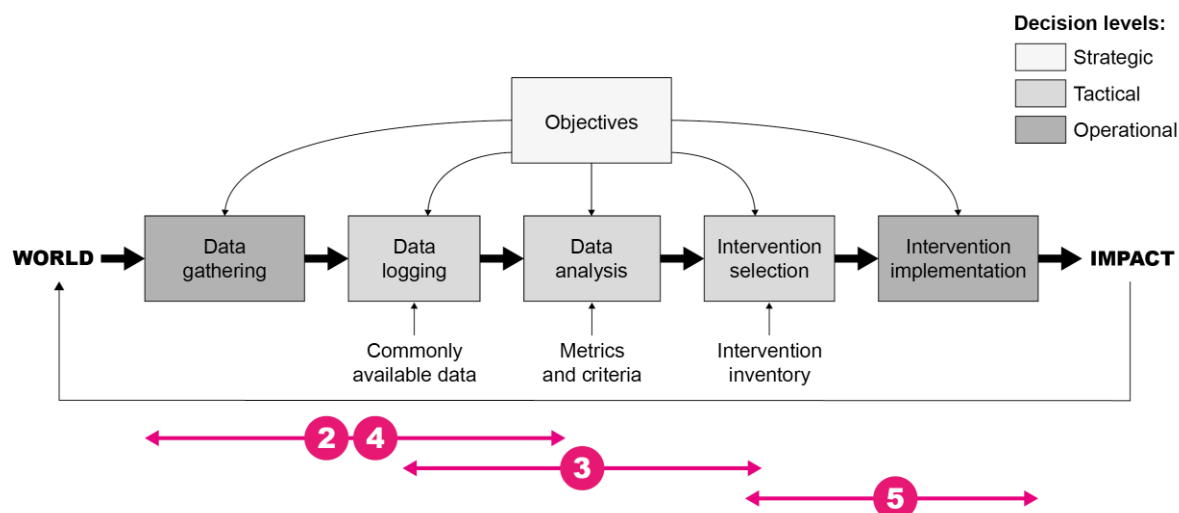


Figure 3 — Sense-plan-act paradigm applied to road management, involvement of CAMBER components 2-5.

2.2 METHODOLOGY FOR SOLUTIONS IDENTIFICATION

This section discusses the principles and process used in identifying and developing solutions for the integration of road safety management and road asset management. Considering the CAMBER pilots vary greatly in terms of road environments and types, road user characteristics, and road authority and governance structures (e.g. municipal vs. regional network coverage, proactive vs. reactive intervention approaches), a one-size-fits-all solution is neither appropriate nor possible. Therefore, a set of solutions was created, jointly addressing the following six project items listed in the grant agreement:

1. how common data can be used;
2. how existing asset management systems and processes can be expanded to incorporate safety;
3. developing additional functionalities required to include safety;
4. defining synergies in data collection;
5. developing safety and maintenance warrants and metrics for an integrated system; and
6. identification of other functionality to address road manager needs.

The above six items were used to search for potential solutions. CAMBER's Deliverable D2.1 "State of the Art and Gap Analysis" (Cardoso et al., 2025) lists knowledge gaps and key barriers in current road safety management and road asset management processes and technologies. To ensure that these findings inform CAMBER activities, the identified gaps and barriers were used as sources of inspiration for the idea generation process.

Once an initial list was created, similar or overlapping ideas were clustered. For example, three partners independently drafted ideas on using mobile cameras, video detection, and webcams, all of which were centred around integrating safety in road asset management. The resulting set of 16 ideas was further developed into solutions. At this point in the project, "development" refers only to outlining the solutions at a high, conceptual level, rather than designing or building them. The aim here is to describe each solution with just enough detail to support the planned impact assessment and evaluation work. As such, this minimum description should include: the type of change the solution is expected to bring about, which use cases it applies to, what results or improvements are anticipated, any limitations, and how it might reinforce or interact with other solutions.

2.3 OVERVIEW OF CAMBER SOLUTIONS

2.3.1 SUMMARY OF SOLUTIONS

Based on the detail provided for each solution in Annex 1, many solutions address gaps related to data availability, data standards, data incompatibility, lack of standardisation and use. A number of solutions tackle issues related to secondary roads, in terms of data and road management, traffic and safety engineering and with particular focus on vulnerable road users and improved traffic management.

The limitations identified are particularly related to aspects such as data formats, sparsity, definitions and incompatibility; technological limitations; institutional and organisational issues and user acceptance. This introduces a number of potential risks that may jeopardise implementation unless well scoped and managed.

A short summary for each solution follows, presented in the order of identification.³ More information on the solutions can be found in Annex 1.

2.3.1.1 SOLUTION #1: ROADSIDE CAMERAS

Applications of cameras in road asset management and road safety are plentiful, due to the flexibility of the available camera types. Static and mobile cameras offer differing potential, and their usage profits considerably from recent developments in object detection and tracking.

Static cameras can be a means to accurately acquire the current state of road user movements in a given area, and this reacts in almost real-time to challenges to safety (risky interactions, detection of crashes) and functioning of the infrastructure (blocked paths, traffic jams reaching into the camera domain of vision). In the form of webcams, they may allow for manual inspection/verification of a detected incident at any point and provide data flows to optimise systems of traffic regulation or assess the effectiveness of interventions through detected changes in traffic flows/vehicle movements.

Mobile cameras can be a means to track the safety of road user interactions (detecting incidents and metrics of safe interaction) and to acquire updates on road infrastructure condition (condition/placement of road inventory and/or pavements).

2.3.1.2 SOLUTION #2: INTEGRATING AND VALIDATING MULTIPLE DATA SOURCES FOR CORRELATION, RELIABILITY, AND VALIDITY

Linking all available and relevant data sources used for road traffic, road safety and asset management. Redefining evaluation and performance criteria. We will establish the feasibility and, where possible, link data from at least the following sources: static/historic and live traffic data, static and dynamic road condition data (including from Flitsmeister or similar, see also 'Contextual information'), road assets and associated data, weather data, road user data and modelling data. The concept aims to improve data reliability and update frequency, enabling faster, data-driven decision-making and reducing the risk of late maintenance detection or overlooked safety issues.

Common data (e.g. map-based information) could provide contextual information to abstract user reports of hotspots or other issues. For example, if a button in Flitsmeister is used to indicate 'road surface quality issue', then apart from the GPS coordinate, nothing is known about the circumstances. The urgency for repair may be higher at a busy intersection (requiring knowledge of volumes and of the intersection) than elsewhere. Note: Digital Twins may be used to show such augmented (contextual) information.

2.3.1.3 SOLUTION #3: SPATIAL SPECIFICATION

Map features relevant to RSM and RAM into a common (spatial) frame of reference to easily explore interrelations and use features relevant to both. For instance, road condition properties might well be safety relevant via implied braking distances or the presence of road surface damage. In turn, safety-

³ Seeing that the identified solutions often relate to multiple project proposal items and CAMBER components, no further grouping was applied when listing the interventions.

relevant data like vehicle movements/IMU data/floating vehicles data can be an indicator for predictive maintenance and thus contribute to RAM.

The integration with digital twins necessitates the spatial specification and also provides the highest level of integration, which can benefit simulations and evaluations of interventions for both RAM and RSM.

2.3.1.4 SOLUTION #4: DATA/METRICS DICTIONARY

This idea focuses on improving the quality, consistency, and usability of infrastructure and safety-related data by developing standardised metrics and integrating novel data sources into road safety and asset management practices.

The approach promotes a more proactive safety management model through the creation of clear, data-driven indicators supported by emerging sources such as crowdsourced pavement condition data. Furthermore, it aims to enhance the relationship between traditional road infrastructure condition indicators and new data-generated indicators, thereby enabling a more comprehensive and evidence-based understanding of road performance and safety conditions. Relating novel indicators to those currently used facilitates a smooth transition from traditional practices to digital RSM and RAM frameworks.

2.3.1.5 SOLUTION #5: DIGITAL TWINS: VALUE AND REQUIREMENTS

This idea defines how DTs can add practical value to existing road asset and safety management systems. Many road authorities already use partial models, so the DT's value must be clear, targeted, and flexible. The approach promotes modular, switchable functionalities. This enables DTs to operate at varying levels of detail and integration, depending on the availability of data and user needs.

DTs can be employed in different phases of the road network life cycle, including planning and design, construction and completion, operation and maintenance, and demolition and reconstruction (Yan et al., 2025). In addition, contributions to road traffic management aspects can also be expected through the implementation of a digital twin (e.g. Aloupogianni et al., 2024; Kamal et al., 2024).

2.3.1.6 SOLUTION #6: ORGANISATIONAL INTEGRATION OF ROAD ASSET AND ROAD SAFETY MANAGEMENT

A perception exists that a number of functions within road authorities structures make use of similar data sources but for different purposes. The responsibilities of these departments are very different although it may be feasible and more efficient if there was better coordination, possibly even integration, of responsibilities and functions. If integration is not possible, at least achieve better coordination between RA, RT and RS management departments to improve more efficient use of resources and greater effect on traffic management and safety.

2.3.1.7 SOLUTION #7: SYSTEM SPEED

This idea is for the development a *lightweight data-exchange layer* between RSM and RAM systems that identifies and shares only essential subsets of data needed for cross-functional decision-making. This ensures that integration enhances coordination without slowing system performance. The layer can also support configurable *decision-making scenarios* to adapt risk reporting and intervention proposals to each authority's speed and policy context.

2.3.1.8 SOLUTION #8: CURVE PARAMETERS

Share curvature and curve quality parameters (e.g. radius, delineation, CAMBER) from RSM systems with the road safety analysis team. These data directly inform iRAP risk models, where sharper or poorly delineated curves significantly increase crash risk for vehicle occupants, motorcyclists, and cyclists. Integrating such data enables more precise network risk mapping and prioritisation of high-risk curves.

2.3.1.9 SOLUTION #9: INTERDISCIPLINARY CBA – FRAMEWORK FOR EVALUATING THE INTEGRATED VALUE OF NOVEL DATA SOURCES

This idea proposes developing a structured framework to assess the costs and benefits of novel data sources, such as connected vehicle and across all relevant domains/systems (RSM, RTM, RAM). The goal is to shift from evaluating each data source in isolation, and instead measure its holistic value in supporting integrated, data-driven road management.

2.3.1.10 SOLUTION #10: WORK ZONES

Digital information related to work zones – such as precise location, geometry, duration and dynamic status (e.g. lane closures, reduced speed limits or worker presence) – can be used to enhance road safety. When shared in real-time with connected vehicles, infrastructure systems and navigation services, this information enables early warnings, automated vehicle adaptation and optimised traffic management around work zones. This reduces risks for both road users and workers by improving awareness, predictability and reaction time in complex temporary traffic situations.

2.3.1.11 SOLUTION #11: LOCATION-BASED PROBING – MAPPING THE SPREAD OF DETECTED PROBLEMS THROUGH TARGETED USER PROBING

This idea suggests actively probing road users near a detected problem to determine whether the issue also exists beyond the initial location, effectively mapping the spatial spread or recurrence of road problems. By asking targeted users in the vicinity about the same issue, the system can confirm if a local defect has network-level implications.

2.3.1.12 SOLUTION #12: CCAM AS MOBILE SENSORS

This idea focuses on leveraging vehicles equipped with CCAM technologies as mobile sensors that continuously collect data on road conditions, traffic flow, and driver behaviour. These data can be integrated with information from RSUs.

These data streams enable a transition from traditional, reactive or scheduled maintenance to dynamic, data-driven asset management. Using ML and big data analytics, it becomes possible to identify crash hotspots, predict potential risks, and guide smarter infrastructure investment decisions.

2.3.1.13 SOLUTION #13: CRASH-DATA INFORMED RSM DECISIONS

This idea focuses on transforming the traditionally reactive approach to asset management, which currently relies on public complaints and staff engineering judgment. While strategic Road Asset Management (RAM) decisions typically address annual maintenance budgets and large-scale maintenance projects, and Road Safety Management (RSM) decisions often draw on accident data, such information is not readily accessible at the operational level.

2.3.1.14 SOLUTION #14: SAFETY MEASURES DURING MAINTENANCE

The idea focuses on integrating proactive safety measures into road maintenance throughout its lifecycle, using real-time monitoring and predictive analytics. It aims to identify and mitigate temporary risks caused by roadworks (which can be implemented through dynamic traffic management, intelligent signage, and feedback from connected vehicles or sensors).

In addition, this idea can be expanded, and maintenance-based DTs can also be employed to predict the correct time for predictive maintenance of the road network.

2.3.1.15 SOLUTION #15: CONTRACT STATUS

This idea proposes focusing primarily on existing contracts and integrating safety and data-sharing obligations into existing maintenance and service contracts to minimise excessive administrative stages and bureaucracy. Changing existing contracts to include new terms of reference or conditions may be challenging in some instances, but should be pursued nonetheless. This solution should therefore also focus on all new contracts. Terms and conditions covering activities related to the integration of asset, safety (and if necessary, traffic) management can be included as standard items in new contracts.

It also highlights the importance of considering the contractual and administrative context when selecting and implementing interventions, which can correspond to RSM and RAM. The legal status of an intervention, whether it falls under an active contract or requires a new process, can significantly affect the time-to-implementation and overall cost. Differentiating between single and framework contracts helps improve planning efficiency and cost forecasting.

2.3.1.16 SOLUTION #16: CRASH PREDICTION AND RISK MODELLING

Risk mapping based on localized road user movements data and crash data can be a new means to improve road safety proactively. Given the potential of floating vehicles data, there might be considerable statistical power available to localize and deal with risk spots on the road infrastructure, based on risk model calibrated to real (or in principle also simulated) crash data. Such a methodology could also be applied to road maintenance aspects, provided indicators of road condition deterioration are obtained and the relation to floating vehicles data is explored.

Provided a digital twin of the area in question has been set-up even more complex interactions with the road environment could be investigated.

2.3.2 MAPPING SOLUTIONS TO CAMBER COMPONENTS

As shown in Table 1, each of the project items has contributed to the solution identification process. When multiple items were at the basis of a solution, this was because two or more ideas (each originating from a separate project item) showed large overlap and were hence combined into one solution.

Table 1 — Overview of CAMBER solutions and their relation to project items and CAMBER components.

#	SOLUTION	PROJECT ITEMS						CAMBER COMPONENTS				
		1	2	3	4	5	6	1	2	3	4	5
1	Roadside cameras	X			X			P	Y	P	P	P
2	Combined data sources ⁴	X			X	X		Y	Y	P	P	N
3	Spatial specification		X	X	X			Y	P	P	P	P
4	Data / metrics dictionary		X	X		X		Y	Y	Y	Y	P
5	Digital twins: value & requirements		X	X				P	Y	Y	Y	N
6	Organisational integration ⁵		X	X		X		Y	Y	Y	P	Y
7	System speed		X	X			X	Y	P	P	N	N
8	Curve parameters	X						Y	Y	Y	Y	N
9	Interdisciplinary CBA ⁶	X						Y	Y	P	P	N
10	Work zones	X						Y	Y	P	Y	N
11	Location-based probing ⁷				X			Y	Y	P	N	P
12	CCAM as mobile sensor				X			Y	Y	P	Y	P
13	Crash-data informed RSM decisions		X	X			X	Y	Y	P	N	P
14	Safety measures during maintenance						X	Y	P	P	P	Y
15	Contract status					X		Y	N	P	N	Y
16	Crash prediction and risk modelling					X		P	Y	P	Y	N
	Total	5	6	6	5	5	3	Y:13 P:3	Y:12 P:3	Y:4 P:12	Y:6 P:6	Y:3 P:6

Note: X = Project proposal item applies. Y = Yes, N = No, P = Partially. Project proposal items: 1 = Common data usage; 2 = Expanding existing RAM systems to incorporate safety; 3 = Additional functionalities required to include safety; 4 = Synergies in data collection; 5 = Safety and maintenance warrants and metrics; 6 = Other functionalities to address road manager needs. CAMBER components: 1 = integrated RAM and RSM; 2 = New-generation data sources; 3 = Digital twins; 4 = ADAS performance; 5 = Low-cost safety interventions.

⁴ Full name: ‘Integrating and validating multiple data sources for Correlation, Reliability, and Validity’.

⁵ Full name: ‘Organisational integration of road asset and road safety management’.

⁶ Full name: ‘Interdisciplinary CBA: framework for evaluating the integrated value of novel data sources’.

⁷ Full name: ‘Location-based probing: mapping the spread of detected problems through targeted user probing’.

Furthermore, Table 1 shows that all CAMBER components are being addressed by the joint set of solutions. The project team found a particularly strong relation between the solutions and Component 1 (Safety-integrated maintenance systems and processes; 13x 'Yes') and Component 2 (New-generation data sources; 12x 'Yes'). In contrast, the solutions were more often partially associated with Component 3 (Digital twins; 12x 'Partially') and Component 4 (ADAS performance; 6x 'Partially'), although direct links were still observed (4x and 6x 'Yes', respectively). Component 5 (Low-cost safety interventions) has received relatively little attention across the identified solutions, but this is to be expected, as an inventory of low-cost safety interventions is the main focus of Chapter 3.

2.3.3 MAPPING SOLUTIONS TO SYSTEM INTEGRATION TYPES

Integration between road safety management (RSM), road traffic management (RTM), and road asset management (RAM) systems can be described at three hierarchical levels: strategic, tactical, and operational (see Section 2.1). In Annex 1, the integration types have been noted for each solution with a pre-defined syntax, in which the systems (RSM, RTM, RAM) are addressed in a fixed order, separated by commas. For example, "{Tactical/Operational_in, X, Tactical}" (Solution #13) corresponds with two types of integration: 1) between the tactical levels of RSM and RAM, and 2) between the operational input level of RSM and the tactical level of RAM. The 'X' indicates that no integration with RTM is foreseen.

Catering to CAMBER component 1 (safety-integrated maintenance systems and processes), the following overview focuses exclusively on the integration between RSM and RAM.⁸ Each solution was found to correspond with between one and four types of integration (e.g. aforementioned example features two distinct types of integration). A frequency table was created to count the total number of solutions per integration type. A visual representation of this frequency table is shown in Figure 4.

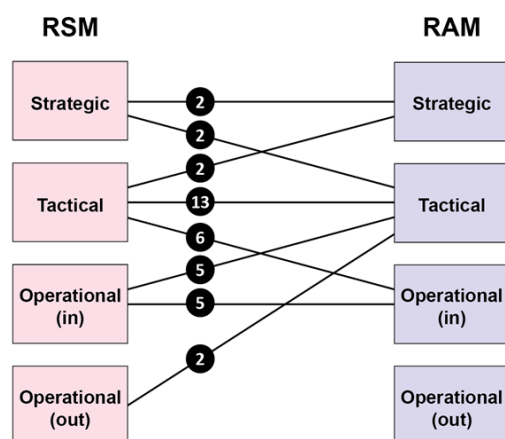


Figure 4 — Number of solutions (total $N = 16$) involved in integration between road safety management (RSM) and road asset management (RAM) systems at three hierarchical levels (strategic, tactical, operational).

⁸ Solutions featuring integration between RSM and RAM may also involve integration with RTM at one or more hierarchical levels. Such integration with RTM has been excluded from subsequent analysis to maintain a focus on CAMBER component 1.

All in all, Figure 4 demonstrates that most combinations between the RSM and RAM hierarchical levels have been covered by the 16 solutions identified in T2.3, theoretically allowing for near-complete integration of RSM and RAM.⁹ Almost all identified solutions ($N = 13$) are viewed as enabling integration between the **tactical** levels of RSM and RAM. This finding indicates that interdisciplinary decision-making (e.g. intervention selection based on data logging and data analysis) is at the core of the CAMBER solutions. In approximately one-third of the solutions ($N = 5$), data collection (operational input level) in RSM may inform decision-making in RAM (tactical level), and vice versa, data collection in RAM may inform decision-making in RSM ($N = 6$). Joint data collection efforts (i.e. **operational input** in RSM and RAM) are also found in approximately one-third of the solutions ($N = 5$).

Integration at the **strategic** level is found less often ($N = 2$ solutions) compared to integrations at tactical or operational input levels. This is not entirely surprising: the strategic level deals with long term goal setting and addressing such goals at the pilot sites may be only partially attainable within the limited timespan of the CAMBER project. It should be noted that in some countries, strategic goals are set at the nationwide level, which means that the relevance of integration at the strategic level may be less apparent for smaller, local road authorities in these countries. Nonetheless, additional attention to integration at the strategic level is warranted in future work, beyond the CAMBER project.

Finally, a limited number of solutions ($N = 2$) involve the **operational output** level, where in this case decisions made by asset management (e.g. to set up a work zone, to perform maintenance), inform operations by safety management (e.g. informing road users, performing safety inspections). These solutions are of special importance for all infrastructure-related safety interventions selected for pilot site testing (also see Chapter 3), seeing that such interventions typically cannot be implemented without a work zone. The limited number of solutions involving the operational output level could have been the result of a potential background-bias by the T2.3 team members involved in solution identification. If practical experience with implementation of road safety and/or road asset interventions is limited, it may have been more challenging to come up with concrete solutions to integrate RSM and RAM at the operational output level. For the CAMBER project, therefore, it is advisable to try to coordinate such integration by involving pilot site personnel with practical experience in both systems.

The frequency analysis presented in Table 2 and Figure 4 shows that most CAMBER solutions primarily support the tactical and operational levels, with comparatively fewer targeting the strategic level. This distribution reflects both the maturity of the available technologies and the practical constraints identified during the gap analysis in CAMBER deliverable D2.1 (Cardoso et al., 2025). Tactical and operational (input) measures (such as improved data collection, harmonisation, and deployment of digital tools) are more immediately actionable within the scope and timeframe of the CAMBER pilots. In contrast, strategic-level integration requires broader organisational, regulatory, and long-term planning changes that extend beyond the current project boundaries. Consequently, while the CAMBER framework acknowledges the importance of strategic integration, the solutions proposed in this deliverable naturally emphasise areas where the project can deliver tangible, evidence-based improvements within the available duration and resources.

⁹ In Figure 4, the links between hierarchical levels of RSM and RAM can be one-directional or bi-directional, depending on the solution signified by the link. To improve legibility, no stratification of the types of directionality was applied in Figure 4.

3 Identification of low-cost safety interventions

This chapter presents the systematic process used in CAMBER to identify and shortlist low-cost infrastructure-related safety interventions—the focus of Component 5 and a core contribution to achieving the project’s objective of enhancing safety on the secondary road network through affordable, scalable measures. It builds directly on the activities undertaken in Task 2.3, specifically the element concerned with identifying potential safety treatments suitable for testing across the CAMBER pilot sites.

Within T2.3, partners developed an initial long-list of candidate interventions and applied a structured assessment framework—aligned with the PIARC Road Safety Manual—to evaluate their cost-effectiveness, expected crash and severity reduction, feasibility, compatibility, potential adverse effects, and public acceptance, as well as their overall economic justification. This review does not, on its own, determine what will be trialled in the CAMBER pilots. Instead, it establishes an evidence-based foundation that will be complemented by co-creation with the pilot leaders and local road authorities in WP4, ensuring that selected treatments are not only effective but also context-appropriate, operationally feasible, and aligned with site-specific challenges and priorities.

Together, the technical assessment undertaken in T2.3 and the participatory design process in WP4 provide the basis for selecting suitable low-cost interventions for simulation and real-world testing. The comprehensive canvassing, evaluation, and documentation of these measures represent an important contribution to KER 7, which will deliver CAMBER’s review of low-cost design features and its recommendations for practical implementation and maintenance on urban and secondary roads. The resulting shortlist presented in this chapter, therefore, serves both as a key input to WP4 and as a substantive component of CAMBER’s knowledge outputs.

This deliverable is the result of preparatory work done in WP2. However, the output in terms of the evaluation of low-cost safety interventions must be seen in context of the CAMBER project as a whole and where these low-cost interventions are closely aligned with pilot testing, ADAS performance and safety performance indicators. Furthermore, while WP2 serves to identify potential low-cost interventions and specifying the evaluation framework, the other Work Packages have equally important roles in defining data requirements and fusion (WP3), investigating solutions and developing specifying digital twin requirement (WP4) and testing these in practice (WP5).

3.1 DEVELOPING A ‘LONG-LIST’ OF LOW-COST INTERVENTIONS

The development of the long-list followed a structured evidence-gathering approach designed to ensure that all relevant, credible, and potentially effective low-cost safety interventions were captured before applying any filtering or assessment. This phase was intentionally broad, drawing on multiple

authoritative sources and leveraging the expertise of CAMBER partners to ensure comprehensive coverage of measures applicable to secondary and urban roads.

The process began with the identification of key reference sources, each assigned to a lead partner responsible for extracting and compiling relevant interventions. These sources included established international road-safety catalogues (such as the *iRAP Road Safety Toolkit*, the *Handbook of Road Safety Measures* (Elvik et al., 2009), and the *SafetyCube Decision Support System*), and regional or national lists of proven low-cost solutions (e.g. Flanders’ ‘quick wins’). It also included interventions emerging from CAMBER’s own analytical work, including:

- The T2.1 and T2.2 literature reviews, reported in CAMBER project deliverable D2.1; and
- The co-creation proposals developed based on the input from pilot teams under T4.1 (see Section 3.2).

Additional sources known to partners (such as *the guide* produced by Spain’s Dirección General de Tráfico (DGT, 2020)) which presents proven, low-cost road-infrastructure measures to improve safety on interurban and conventional roads, aligned with the Safe System approach, were also consulted.

Partners added each identified measure to a shared Excel database, noting the original source to support traceability and later consolidation. These efforts resulted in a list of 313 interventions in total, including potential duplicates (see Table 2).

Table 2 — Overview of the number of interventions identified per source.

Intervention source	Count
iRAP toolkit	71 ¹⁰
SafetyCube DSS	103 ¹¹
Handbook of Road Safety Measures	39
FHWA’s Proven Safety Countermeasures	11
Dirección-General de Tráfico	28
Flanders ‘quick wins’	20
T2.2 literature review	11
T4.1 co-creation proposals	30
Total (including duplicates)	313

¹⁰ Only interventions with a ‘low’ estimated cost were selected from the IRAP toolkit.

¹¹ SafetyCube interventions were taken from deliverables D5.4 (Inventory of assessed infrastructure risk factors and measures) and D6.4 (Inventory of vehicle-related risk factors and measures).

Once all sources had been canvassed, the combined entries were reviewed collectively to identify duplicates, harmonise terminology, and categorise the interventions into coherent groups. This ensured that the resulting long-list was both comprehensive and structured, providing a solid starting point for the subsequent assessment and shortlisting.

This systematic canvassing process ensured that the long-list reflected the full range of internationally recognised, research-based, and context-specific low-cost safety measures—forming a robust foundation for the evaluation and co-creation steps that follow.

3.1.1 ORGANISATION OF THE INTERVENTION LONG-LIST

After the long-list of interventions was made, the interventions were subsequently categorized according to three key dimensions (i.e. Which, Where, What):

1. **Which** Safe System ‘pillar’ does the intervention relate to: safe roads and roadsides, safe road users, safe vehicles, safe speed, or post-crash care? Interventions under Safe Roads and Roadsides aim to improve the physical environment through forgiving road design, roadside protection, and clear visual guidance (e.g. delineation, guardrails, and surface treatments). Measures in Safe Road Users promote safe behaviour through awareness, enforcement, and behavioural-change approaches. Safe Vehicles relates to improvements that enhance vehicle safety or assist driving, including ADAS integration and V2I communication. Safe Speed covers interventions that regulate, influence speed choice and ensure that speeds and speed limits comply with safe speed principles taking into account differences in speeds, mass and direction. Finally, Post-crash Care includes systems that improve emergency response and mitigate injury severity after a crash.
2. **Where** is the intended application environment of each measure? It includes typical network elements and contexts in which interventions can be deployed: intersections, midblocks (road segments between junctions), school zones, pedestrian crossings, cycling infrastructure, motorways, rural roads, urban areas, roadworks zones, transition zones, parking areas, pedestrian facilities, motorcycle facilities, and a category of all locations where a measure may have general applicability.
3. **What** is the technical or functional nature of the intervention? To capture the diversity of possible measures, interventions were grouped into different technical domains: Infrastructure-Geometry, Infrastructure- Surface, Maintenance Measures, Signage and Road Markings, Lighting, Speed Management, Traffic Control, Vehicle-Based Measures, ICT and Data-Driven Solutions, Conflict Point Management, Behavioural Influence, Enforcement, Screening, Infrastructure- Road Restraint Systems, Infrastructure- Roadside Treatment, and Infrastructure-Median Treatment.

In this process, it was found that many interventions overlapped, differing only in terminology or minor implementation details. To address this, comparable measures were grouped under unified overarching interventions. The grouping process was based on a consensus approach in which CAMBER-partners reached agreement as to which interventions could be grouped. Items that were too broad, unclear, or not related to interventions affecting road infrastructure —such as behavioural or regulatory measures—were excluded to maintain alignment with CAMBER’s focus on low-cost infrastructure solutions. CAMBER partners then reviewed and refined the groupings, adding missing descriptions, confirming the which/where/what classifications, and validating the overarching titles.

Once confirmed, every single intervention was given a structured code. This coding system allows interventions to be efficiently filtered and queried according to specific aspects or combinations of interest, such as location type, intervention function, or safety pillar.

Since each intervention can be associated with multiple where and what categories, this provides flexibility to represent and filter the interventions within a unified classification structure. This also enables road authorities and researchers to understand not only the functional purpose of each intervention but also its spatial relevance and technical nature.

3.2 EVALUATION AND CO-CREATION

The CAMBER framework uses seven assessment dimensions (or criteria) for the operationalisation of the interventions—four *screening criteria* (i.e. feasibility, compatibility, public acceptance, and benefit–cost ratio) and three *performance evaluation criteria* (i.e. crash and severity reduction, cost-effectiveness, and effects on other road users).

In this framework, *screening criteria* act as overarching conditions that determine whether an intervention is viable and appropriate within the local physical, organisational, regulatory, and socio-political context. Interventions that clearly fail one or more criteria are unlikely to progress to pilot testing. *Performance evaluation criteria*, by contrast, describe performance characteristics that enable comparison, prioritisation, and refinement of the interventions that pass the initial screening. They capture the expected safety impact, economic efficiency, and potential side-effects for different user groups.

Together, the criteria provide a transparent and consistent basis for confirming that co-created intervention choices are feasible, context-appropriate, and aligned with CAMBER’s safety and asset-management objectives.

The assessment of each of the selected interventions is discussed in later sections of this chapter. Details for each selected intervention level can be found in Appendix 2. Appendix 2 gives detailed insight into the application of the 7 assessment dimensions and facilitates the pilot sites in CAMBER in selecting interventions most appropriate to local conditions. Furthermore, the pilot sites can take into account known constraints as identified by the assessment (e.g. relating to supporting evidence, cost effectiveness). Important to note is that pilot sites choosing interventions with limited evidence of effectiveness, can choose to further investigate the feasibility of implementing these in WP4. In WP4 a limited number of interventions will be tested in (driving) simulator environments and this can serve as an additional filter prior to actually implementing the interventions in a pilot environment. Of utmost importance, and despite the degree of evidence related to efficacy, pilot sites will need to perform thorough evaluations and document the findings so as to build on current knowledge.

3.2.1 OPERATIONALISATION OF SCREENING CRITERIA

The screening criteria below are presented in no particular order. When the criteria are applied successively on a list of interventions, the order in which the criteria are applied may influence the efficiency of the screening operation. Ideally, a criterion that requires little information gathering effort while yielding a large reduction in the number of eligible interventions is chosen first. This way, only few interventions necessitate gathering harder-to-obtain information on subsequent criteria.

3.2.1.1 FEASIBILITY

For feasibility, one needs to respond to whether it will be possible to install the intervention at this location (including issues relating to physical constraints, sight distance, etc). In addition, feasibility refers to the overall practicality of implementing a selected low-cost safety intervention at a pilot location under existing infrastructural, regulatory, and operational conditions. It concerns the collective assessment of factors that determine whether an intervention can be realised without excessive modification of existing infrastructure, undue disruption to traffic, or violation of safety or design standards (PIARC, 2025).

In the CAMBER framework, feasibility acts as a screening filter, as interventions that are unlikely to be realisable due to physical, regulatory, or temporal constraints should be excluded from further cost-effectiveness or cost-benefit analysis. To operationalise feasibility for the five pilot sites, the following aspects will be jointly considered for each proposed intervention:

- **Operational and maintenance considerations:** Determine whether the intervention can be operated and maintained using existing resources and within current maintenance cycles (Borghetti et al, 2024).
- **Physical and geometric considerations:** Evaluate whether the intervention can be accommodated within the existing cross-section, alignment, and available space with minimal reconstruction requirements (Ziakopoulos & Yannis, 2020).

All the above aspects are based on pass/fail criterion. Feasibility outcomes will not be based solely on isolated criteria, but rather on a comprehensive judgment that balances the above aspects. Interventions demonstrating major constraints in one or more domains may be excluded at this stage to ensure that subsequent economic and effectiveness evaluations focus only on realistically implementable measures.

3.2.1.2 COMPATIBILITY

Compatibility refers to the suitability of different elements, products, or processes to be used together in a road management system to meet specific requirements. This applies to ensuring systems and strategies can work harmoniously, such as aligning safety standards with design, or coordinating different asset management activities across the whole asset lifecycle.

Compatibility ensures that short-term decisions (like cost savings) are consistent with long-term goals (like safety and operational performance) by using a system-wide perspective and a multi-disciplinary approach to balance different objectives.

Compatibility is essential for ensuring that different parts of a road management system, such as data management, performance monitoring, and risk analysis, can work together effectively to achieve organisational goals. In CAMBER, this is ensured through close collaboration with the pilot sites and the planned stakeholder engagement.

3.2.1.3 PUBLIC ACCEPTANCE

Public acceptance refers to whether an intervention will be accepted by the community and endorsed by decision-makers. Additionally, the potential for non-compliance must be gauged, considering factors such as patterns of road user behaviour affected, technical implementation requirements, and enforcement mechanisms.

This can be evaluated by analysing the perspectives of various stakeholders, including the road users, road administration authorities, and higher-level decision-makers. Surveys and questionnaires, as well as interviews and focus group discussions, can be used to this end.

Key factors influencing acceptance include the level of knowledge and awareness of the intervention, the specific hazard it addresses, the perceived effectiveness and fairness of the intervention, its impact on individual freedom and privacy, and the extent to which it aligns with prevailing social norms. The literature on this subject shows few references, most focused predominantly on speed-related interventions. Indeed, acceptance is context-sensitive, as it depends on demographic characteristics (e.g. age, income, and mode of transport) and cultural factors.

In selecting candidate interventions for testing in CAMBER, a key criterion is acceptance by pilot road administrations, this being dependent on confidence in each intervention's effectiveness, legal and political constraints, as well as compatibility with the project's duration and operational framework.

3.2.1.4 BENEFIT-COST RATIO

Cost-benefit analysis (CBA) evaluates the economic viability of a solution and is an important metric for building business cases through road safety appraisal. By comparing the expected benefits of a solution with the associated costs of implementation, road authorities can understand the potential return on investment. A summary of CBA and its intended application in CAMBER is given in Sections 4 and 5, respectively **Error! Reference source not found.**

Before implementing a solution, CBA is used as a decision-making and prioritisation tool. Road authorities should make use of the best evidence available in research literature to understand the likely costs and benefits if the solution is implemented on their road network. An important further consideration is what to include in the CBA. It is usual for CBA of road safety interventions to concentrate on the benefits in terms of road crashes accruing from the intervention and the cost of the intervention itself (implementation and maintenance). In some instances, it may also be prudent to include (dis)benefits in terms of traffic operations, specifically aspects such as travel times which include stops and delays before and after implementing the intervention. There are several sources of information on CBA for well-established interventions, for example, enforcement and behavioural interventions such as seat belt wearing or infrastructural interventions such as speed humps and those listed in Section 4. Road authorities should decide the time-period over which a CBA score is most informative – a first year rate of return (FYRR) metric, together with CBA over the expected lifecycle of the solution, can give a good indication of economic viability. A CBA score of more than 1 indicates that the solution will provide greater economic benefit than cost and is a useful threshold to use as a criterion for initial selection.

After implementing a solution, CBA is important to understand whether the likely financial return is as expected, and the economic viability of the solution if implemented on a wider scale. Data gathered following implementation should be used to evaluate safety (and other) benefits, which can be monetised. Comparing this with actual implementation costs and ongoing maintenance costs (which account for the local context and may be different from those given in the literature) gives a CBA score.

3.2.2 OPERATIONALISATION OF PERFORMANCE EVALUATION CRITERIA

3.2.2.1 CRASH AND SEVERITY REDUCTION

CAMBER Pilot sites must decide which interventions to test and how to deploy them effectively. This requires a systematic approach that connects evidence of risk, local feasibility, and Safe System principles — ensuring each intervention reduces crash likelihood and severity while avoiding adverse side effects. In order to address crash severity reduction, each pilot site must determine what “crash and severity reduction” means - i.e. is the goal to reduce frequency of specific crash types (e.g. run-off-road, pedestrian, rear-end), reduce impact speeds or crash energy exposure, improve visibility, predictability, or driver/cyclist behaviour, etc – based on acceptable definitions within the project. The Pilot sites are to compile a list of interventions that address the site’s dominant crash and severity risks, considering engineering measures, operational/technological measures and/or behavioural / enforcement. This helps operationalisation by encouraging a multi-domain approach to crash and severity reduction and prevents one-dimensional solutions.

3.2.2.2 COST-EFFECTIVENESS

Cost effectiveness analysis (CEA) compares the cost of implementing a measure with the benefits in terms of crash or casualty reduction. It is very similar to CBA, except that the crash or casualty reduction benefits are not monetised. A typical outcome indicator for cost-effectiveness analysis is the number of crashes or casualties prevented per unit cost.

This metric is useful as a ‘rank order’ attribute, as it is difficult to determine a sensible threshold if used as a criterion for selection. In road safety, the effects of most road safety measures are relatively well documented and, taking into account potential transferability issues, generally applicable as a first-order estimate of expected effects when prioritising road safety interventions. By expressing the potential crashes saved in terms of investment cost per intervention, a rank order can be determined, and the most cost-effective measure selected. Authorities should establish a consistent spatio-temporal horizon through which to compare the cost-effectiveness of different interventions. Cost-effectiveness is also a function of the broader goals and parameters within which an authority is working. For example, some interventions may be more cost-effective when targeting particular road user groups, or within budget constraints. Therefore, determining what “cost-effectiveness” means is an important starting point.

Information on potential crash and severity reduction should be obtained from the literature. Road authorities should seek the most relevant and transferable evidence for the local road safety context. Information on implementation cost can also be obtained from the literature, for example, through the iRAP [*Road Safety Toolkit*](#). Costs should, however, be calibrated according to the local context and specific implementation plan. It is important to consider ongoing maintenance and operation costs in addition to implementation costs.

3.2.2.3 ADVERSE EFFECTS ON OTHER ROAD USERS

As CAMBER pilot sites move from concept to implementation, they must ensure that innovation does not inadvertently increase risk for certain user groups. New technologies, data systems, and infrastructure designs can reshape traffic behaviour, visibility, and accessibility — sometimes in unpredictable ways. It is important to identify, quantify and mitigate unintended harms to vehicle

occupants, pedestrians, cyclists, motorcyclists, and other road users before and during intervention deployment, in order to establish a clear decision record (Go/Modify/Pause/Stop), a mitigation plan, and monitoring triggers. This requires moving beyond traditional “crash hotspot” analysis to a broader, proactive understanding of *who might be affected, how, and under what conditions* — before the intervention is even selected or defined.

Before any site or intervention is proposed, pilot sites need to clearly articulate what they hope to achieve (e.g. severity reduction, ADAS readiness, safer cycling connections). Then explicitly identify *who* uses or is likely to use the site — including pedestrians, cyclists, motorcyclists, heavy vehicles, children, and people with disabilities, amongst others. This forces early consideration of user diversity and interaction, highlights vulnerable users who could be unintentionally disadvantaged by design or operational changes, and shapes the data and consultation required for fair assessment.

Pros:

- Promotes inclusive and human-centred planning.
- Reduces risk of bias toward motor vehicle efficiency.
- Builds early alignment around shared outcomes (e.g. Safe System goals).

Cons:

- User exposure data for vulnerable groups may be limited.
- Requires behavioural insight and empathy beyond traditional engineering.

It is also important to assess how the pilot site functions by determine which user groups may be most vulnerable to change and considering traffic and pedestrian volumes, vehicle types, speeds, land-use context, roadside activities, and network role (e.g. freight corridor vs. urban access street). This prevents mismatched interventions (e.g. vehicle-oriented solutions in pedestrian-heavy areas), reveals potential user conflicts and operational pressures and ensures that future interventions are proportionate to risk exposure and local need.

Performing a structured “adverse effects scan” for each potential site or problem area can also be useful to ascertain whether the interventions is likely to shift risk to another user group or location and whether behavioural adaptation could undermine the safety objective. This helps identify latent risks early enough to avoid them through design. In the implementation of the interventions, pilot sites should adopt a whole-system perspective that recognises safety as dynamic — shaped by user behaviour, environmental conditions, data quality, and institutional readiness. The pilot sites should have a clear understanding of user context and risk exposure; an assessment of potential adverse effects before defining any intervention.

These preparatory steps are likely to encourage a whole-system, proactive approach to safety building equity and inclusion into early decision-making and minimising risk of introducing harm or inequity through innovation. However, it requires coordination across multiple disciplines and data systems, is likely to add time and analytical effort before any tangible action and success depends on the team’s capability in multimodal risk analysis.

3.2.3 SELECTION OF INTERVENTIONS VIA CO-CREATION

While CAMBER defines a structured set of criteria for evaluating candidate interventions, the selection process was not purely top-down. Task 4.1 followed a co-creation approach in which pilot partners and

local stakeholders jointly identified the most relevant local challenges and intervention options. This approach yielded a set of 30 interventions, see Table 3.

Table 3 — Interventions identified through co-creating in T4.1.

Intervention category	ID	Intervention name
Intersection Safety Enhancements	1	Mini-roundabouts (raised or marked)
	2	Raised intersection
	3	Edge islands or splitter islands
Road restraint systems	4	Road restraint systems
Post-crash measures	5	Impact sensor installation
In-vehicle warning system	6	Warning system for a school zone/ temporary market/ work zone
	7	Warning system for an unsignalised crossing
Roadside Hazard Mitigation (focus on sharp curve treatments)	8	Advance warning signs with curve symbol and advisory speed
	9	Visual hazard warnings on curves (chevrons, signs)
	10	High-contrast edge and centrelines
	11	Superelevation modification
Signage and Marking Improvements	12	Surface colouring at sharp horizontal curves
	13	Improved sign placement and visibility (retroreflective pavement markings and signing during nighttime)
	14	Advance warning signs for curves, intersections, or schools
Speed Management Interventions	15	Alternating road markings (dragon teeth, coloured markings)
	16	Dynamic speed feedback signs
	17	Speed humps / cushions / tables
	18	Gateways / entrance treatments (e.g. in area transition)
	19	Chicanes or curb extensions
Visual and Perceptual Design Treatments	20	Optical speed bars (transverse pavement markings)
	21	Stone block paving
	22	Coloured surfacing (e.g. red asphalt in conflict zones or cycling paths)
Vulnerable Road User Protection	23	Narrowing lane width via markings (edge lines or centreline shifts)
	24	Peripheral markings to simulate narrowing effect
	25	Cycle lanes with visual separation (paint or colour)
	26	Refuge islands at crossings
	27	Raised or painted pedestrian crossings
	28	Zebra crossings with advance yield markings
	29	In-ground lighting for pedestrian crossing
	30	Warning system for pedestrians crossings

Although presented here in a structured way, the role of the screening and performance evaluation criteria is to formalise and validate the intervention options that have been jointly identified with pilot partners and stakeholders through the T4.1 co-creation process. They provide a consistent framework for confirming feasibility, compatibility, expected safety performance, and economic rationale, ensuring

that interventions emerging from stakeholder dialogue are robust, comparable across pilots, and prepared for evaluation.

3.2.4 REVIEW OF SELECTED PILOT SITE INTERVENTIONS

This section outlines how the findings from the long-list evidence review are applied to the co-created intervention selections for each pilot site. The screening and performance evaluation criteria (see Sections 3.2.1 and 3.2.2) are used to interpret existing evidence, estimate expected impacts, and identify knowledge gaps that the pilots are designed to explore. As mentioned, interventions with limited evidence relating to efficacy need not be automatically excluded from implementation in the pilots. CAMBER WP4 offers the opportunity to introduce a crucial intermediate step, namely testing and validating efficacy of the intervention in a simulated environment. This will provide additional information to motivate the selection of a particular intervention for implementation in a real world (local pilot) situation.

For each of the 30 interventions for the pilots via the co-creation process, the criteria are used to clarify (i) what is already known, (ii) what can reasonably be expected, and (iii) what remains uncertain. Drawing on the knowledge gathered so far in the project (including from the literature review, gap analysis and the low-cost intervention long-list process), each intervention is reviewed to determine:

- the type and strength of evidence available;
- the likely impact in the CAMBER pilot context, where evidence exists;
- the gaps where evidence is weak or absent; and
- the learning opportunities the pilots can generate to address these gaps.

A template was used to consistently and systematically review each intervention (see Annex 2). This approach fulfils the broader objectives of Component 5 to generate new insights into the effectiveness, implementation requirements, and behavioural implications of low-cost treatments on secondary and urban roads. By articulating specific goals and expectations for each intervention, the pilot sites contribute both to local safety improvements and to CAMBER's wider ambition to enrich the evidence base that underpins CAMBER Key Exploitable Result (KER) 7 (a published review of low-cost features in road link and intersection design, recommended infrastructure measures and guidelines for designing, implementing and maintaining different road safety elements for urban and secondary roads with minimal to the surrounding environment).

The target audience for the collected information related to the interventions are primarily the pilot sites themselves. The interventions were independently reviewed by four of the CAMBERCAMBER partners, using a specially prepared review template. To ensure internal consistency, reviews were checked by another partner, and the summarised results are shown in Annex 2. Although some interventions are viewed as well-proven (such as #1, #4, and #27 in Table 3), the evidence base for many others is considered scarce (for example, #5-8, #10, #16, and #23). The template featured a 4-point scale to indicate the strength of evidence (ranging from 0 = none to 3 = strong) for each of the 7 criteria. The average strength of evidence for Feasibility ($M = 2.5$) and Compatibility ($M = 2.1$) was rated as medium to strong. All interventions are expected to be feasible for pilot testing, although some of them require ongoing maintenance (e.g. #8, #9). Some may not apply to urban roads (e.g. #11), whereas other interventions only apply to urban roads (e.g. #21). Several interventions are viewed as compatible with

digital twin asset inventories (e.g. #7, #8, #14, #15, #23, #24, #29). Some are specifically viewed as compatible with other safety interventions (e.g. #2, #19), whereas some other interventions are dependent on implementing other measures, such as enforcement (e.g. #16) or complementary measures (e.g. #26). The strength of evidence for Cost-Effectiveness ($M = 1.6$), Effects on Other Road Users ($M = 1.6$), and Benefit-Cost Ratio ($M = 1.5$) for most interventions was rated as weak to medium at best. This does not imply that the interventions are not suitable for the pilots, but rather that these criteria are not well-documented in the primary research evidence used for the review (i.e. the sources listed in Table 2). In other words, the supporting evidence in the primary sources used in CAMBER provide limited evidence of the efficacy of these interventions as measured by the applied criteria.

The CAMBER partners involved in reviewing the interventions pointed out that the interventions were conceptually aligned with mechanisms supported in the sources. Therefore, limited evidence on a particular criterion can be viewed as an opportunity for CAMBER to pay specific attention to these aspects as part of the pilot evaluation. Equally important is that specific attention be paid to providing well-documented research findings as part of the pilot evaluations, thereby advancing the current state of knowledge.

4 Impact assessment

Impact assessment of the proposed solutions forms a critical part of evaluation activities within CAMBER. The impact assessment in CAMBER serves to:

- Inform the selection and development of solutions across the five components (for example, the selection of interventions – see Section 3 and the development of the digital twin roadmap (WP4, T4.5)).
- Understand the socio-economic benefits of solutions developed and tested within pilot sites (WP5, T5.3).
- Estimate the potential benefits of solutions developed within CAMBER if they were to be adopted on a larger scale (WP5, T5.4).

T2.4 aimed to develop the methodology and plans for impact assessment in CAMBER and consisted of the following activities:

- a) Agreement on the **scope** and desired **outputs** of impact assessment in CAMBER
- b) Review of the existing **sources** and **methodologies** which may support impact assessment in CAMBER
- c) Setting out the **theoretical principles** for conducting impact assessment in CAMBER
- d) Setting out the **plans** for conducting impact evaluation across the different elements of the project

This chapter describes the activities and outcomes relating to tasks a), b), and c) above. The plans for CAMBER are further elaborated in Section 5, taking outputs from the evaluation framework.

4.1 DEFINING THE SCOPE AND DESIRED OUTPUTS

All partners contributed to discussions on the scope of the impact assessment and the outputs required. There was considerable discussion about the CAMBER components and the feasibility of performing impact assessment across each of these. Several points were raised:

- Firstly, there was a need to clarify which impacts are within the scope of CAMBER. The project has a broad set of aims relating to safety and asset management. For impact assessment to be effective and methodologies developed in CAMBER to be replicable beyond the project, it is not feasible to incorporate all potential impacts relating to the developed solutions.
- Secondly, the components do not function in isolation, and there are often significant dependencies between them. This is demonstrated by the fact that all the solutions listed in Table 1 cover multiple components. For example, static cameras may be directly an infrastructure intervention (Component 5), but the outputs can be used to inform digital twin creation, and the use of this data could support both asset and safety management interventions. Therefore, components should not be considered in isolation for impact assessment.

- Thirdly, the impacts relating to each component will vary, as will the level of obtainable evidence. Certain impacts are difficult to quantify accurately or to monetise for the purposes of CBA. For instance, measuring the impact on crash reduction of more efficient decision-making based on real-time data will be challenging. There may also be challenges with obtaining data at pilot sites, and the availability of data may vary by pilot site.
- Fourthly, crash risk assessment and economic evaluation through CBA is well established in road safety for infrastructure interventions (such as within Component 5) yet is significantly more challenging for solutions developed within the other components (as above, it is complex to link the implementation of a new data source or digital twins to an improvement in crash risk).

To support with addressing these challenges, a decision tree (see Figure 5) was developed to classify the impacts of developed solutions across all the components and to understand the relationships between them.

CAMBER IMPACTS DECISION TREE T2.4 & T2.5

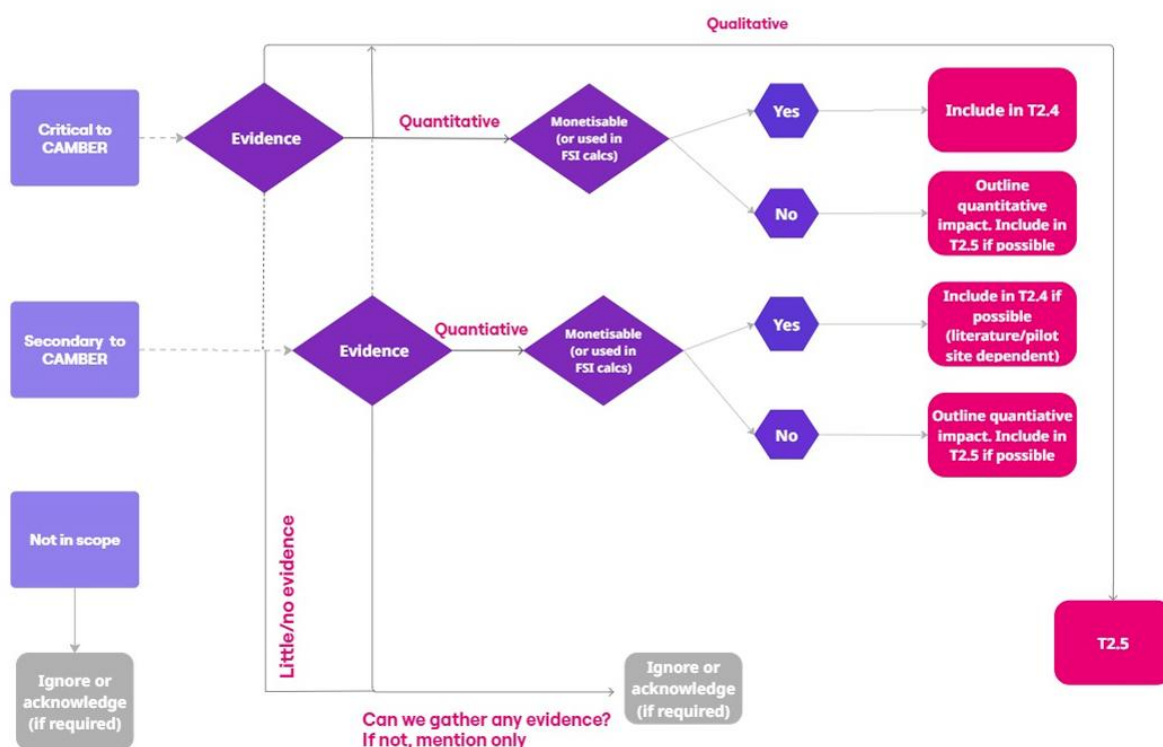


Figure 5 - Decision Tree for classifying impacts across the CAMBER components.

The decision tree distinguishes between impacts that are critical to CAMBER, secondary to CAMBER, and those that are not in scope. It guides partners through a logical pathway based on the availability and type of evidence (quantitative or qualitative) and whether the evidence is monetisable or applicable in Fatal and Serious Injury (FSI) reduction calculations.

For instance, it is anticipated that quantitative evidence relating to CBA or FSI calculations will be available for several impacts in CAMBER. These include traffic and speed measurements, road user behaviour metrics, benefits of new data (for example improved availability and update frequency), operational efficiency (for example relating to maintenance schedules) and costs (for example to operate a digital twin). The impacts for each component are discussed further in Section 5. Impact indicators listed by component (for example in Section 5.2.3.3 for Component 1) have been considered according to their position in the tree. The impact indicators and their inclusion within the impact assessment will be understood further as data is collected and evidence gathered through WP3, WP4 and WP5.

When evidence is purely qualitative, such as insights pertaining to driver attitudes or social norms influencing road user behaviour, there was consensus among CAMBER partners to evaluate these under the general evaluation framework. In cases where an aspect is deemed critical (or secondary) to CAMBER but little or no evidence exists, the framework encourages partners to first determine whether additional data can be gathered. If that is not possible, such impacts should still be acknowledged in reporting to ensure transparency and comprehensiveness.

The decision tree provides a coherent framework to ensure consistency in how impacts are prioritised, categorised, and evaluated across CAMBER's tasks, enabling a balanced integration of quantitative rigour and qualitative insight.

The impact assessment at the pilots will be focused on 'solutions' (that could span multiple components) rather than individual components, and impacts relating to these solutions should encompass all relevant components. Some impact assessment activities during CAMBER will relate specifically to one component, for example, the digital twin roadmap (WP4, T4.5). However, where possible, these assessment activities should also account for benefits and costs realised across other components. Creativity is needed to assess some of the components where economic assessment is less well established within road safety.

In terms of the specific approaches and outputs desired for CAMBER, the impact assessment will focus on the socio-economic evaluation of solutions developed and implemented through CBA and FSI analyses. These are described in detail in Section 4.3.1 and Section 4.3.2. The main output indicators for measuring impact will be:

- CBA scores with associated Net Present Value (NPV) – calculated through comparing the costs of implementing the solutions with the monetary benefits associated with the safety improvements they generate
- Estimated FSI reductions – calculated using standard approaches, such as iRAP's methodology
- CEA scores (where beneficial in addition to the above)

When considering the cost of implementation of solutions for CBA calculations, this should include:

- Material costs (equipment, supporting (digital) infrastructure)
- Operational costs (resources, wages)
- Maintenance costs (beyond the initial implementation)

The CBA and FSI approach should allow for comparability between pilot sites but also be flexible as to incorporate variation in applied solutions.

Surrogate safety measures (SSM) will be an important part of the impact assessment at pilot sites. It will not be feasible to use crash or casualty data to robustly evaluate the effectiveness of implemented solutions due to, for example, project timescales and the limited sample size of such datasets. FSI calculations will make use of risk indicators to estimate the FSI reductions associated with implementation of the solutions. The assumptions and limitations relating to the application of methodologies will be listed carefully.

The uncertainty in FSI and CBA estimates should be captured where possible by presenting a range of estimates, and sensitivity analysis used for understanding the impact of different parameters. The specifics of how uncertainty will be applied to pilot sites are dependent on the data available. For example, ranges of costs will be used if this information is available and different scenarios will be considered for FSI calculations where there is uncertainty in the input data following pilot site implementation. Where there are multiple solutions which may be having an impact on different outcome measures, interactions and potential double counting will be accounted for.

4.2 METHODOLOGY REVIEW

To identify suitable methodologies for impact assessment through CBA and FSI analyses, CAMBER partners undertook an extensive review of relevant sources and methodological approaches outlined in the literature and utilised for other projects. The objective of this review was to understand the range of existing approaches to quantifying and monetising impacts, and their potential applicability within CAMBER. Sources were filtered according to their relevance to CAMBER and the component(s) to which they related. This task was performed alongside task a) to inform the discussions about the scope and outputs. The review also served as a useful input to the development of the evaluation framework (see Section 5).

During the initial review phase, partners collectively identified 22 relevant sources. Most of these sources were associated with Component 5, which reflects the well-established practice of CBA and FSI analyses for evaluating infrastructure-related interventions. Core CBA frameworks, including the iRAP methodology, European Road Safety Observatory (ERSO) CBA guidelines, European Common Evaluation Methodology Handbook for CCAM, and SafetyCube methodology, provide foundational principles for economic evaluation and impact quantification. Road safety assessment approaches, such as iRAP star ratings (iRAP, n.d.) and Infrastructure Risk Rating (NZTA, 2024) offer standardised approaches for evaluating infrastructure safety levels that can help with baseline assessments at pilot sites.

Several sources outlined methodologies tailored to specific (vulnerable) road user groups. These included frameworks for assessing pedestrian crossings (Basile et al., 2010), cycling infrastructure (Wijlhuizen et al., 2014), and deriving risk estimates for motorcyclists using dynamic data (Hula et al., 2021). Proactive risk identification methods, such as Data Envelopment Analysis (Fancello et al., 2020) and risk indexing approaches that do not rely on historical crash data (de Leur & Hill, 2015), were also identified.

One particular focus of the review was to gather updated guidance on crash cost estimates and benefit valuations within European contexts. Several recent sources were particularly useful (Daniels et al., 2019; Wijnen et al., 2019) and further discussions with the SafetyCube and iRAP teams helped to clarify the best approach according to current research. This is further discussed in Section 4.3.1.

In contrast, only a limited number of sources addressed CCAM and ADAS, and none were identified relating to digital twins. Recognising this gap, a second, more targeted review was conducted to capture a broader set of methodologies and evidence sources relevant to all CAMBER components. This subsequent phase expanded the evidence base to 53 sources, including studies drawn from cross-sectoral fields such as construction and organisational change — areas offering transferable insights due to limited established approaches within the road safety domain, particularly for DTs. The complete list of sources reviewed by partners is outlined in Annex 4.

The additional 31 sources identified in the second phase addressed these gaps across several thematic areas. For ADAS evaluation, sources included the V4Safety CBA tool (Wijnen, 2025), retrofit effectiveness of ADAS (Pizzicori et al., 2025), and methodologies for quantifying monetary and prospective benefits of utilising ADAS systems (Feig et al., 2017; Masello et al., 2022). Bützer et al. (2022) discuss a CBA tool for evaluating ADAS developed in the VIRTUAL project. However, this tool is still reliant on discussions of each individual ADAS, with cost inputs required from users. Additionally, Aleksa et al. (2024) performed a CBA on ADAS utilising a CBA tool and highlighted crash reductions associated with ADAS.

For CCAM assessment, sources were identified referencing real-world European pilots that provided socio-economic evaluation frameworks for Automated Driving Functions (ADF) and C-ITS deployment, demonstrating quantified safety, efficiency, and environmental benefits (Asselin-Miller et al., 2016; Bjorvatn et al., 2021; Mitsakis et al., 2018; Studer et al., 2023).

Additional general CBA guidance was identified, including the PIARC Road Safety Manual (PIARC, 2024), EU-approved investment appraisal methodologies (European Commission, 2014; Sartori & Marra, 2021), and comprehensive reviews offering CBA approaches based on available evidence types and data quality (Putatunda et al., 2025).

To address the digital twin gap, partners identified digital twin economic assessment studies demonstrating quantified benefits across transport and construction sectors, including lifecycle cost savings and operational efficiencies (Department for Transport & Arup, 2024; Karunaratne et al., 2025; Thomas, 2024; Yan et al., 2025). Digital twin evaluation frameworks and maturity models offered structured approaches for assessing platform capabilities (Tang et al., 2025; Uhlenkamp et al., 2022).

Given CAMBER's integrated approach, the review incorporated cross-sectoral sources on data integration evaluation, asset management frameworks, and organisational implementation costs, recognising that hidden costs such as training and change management must be captured to ensure realistic CBA outputs (Armstrong, 2002; Goodhue et al., 1992; Phillips-Wren et al., 2009). Studies on wider benefits provided approaches for capturing indirect effects such as time savings, emissions reductions, and vehicle operating costs alongside direct safety impacts (Byaruhanga & Evdorides, 2024; Thiessen et al., 2017).

Across both review phases, several reputable sources were found that outline principles of CBA applicable to different contexts and components. However, relatively few provided quantifiable or monetisable evidence of impacts suitable for direct use in CBA or FSI reduction calculations. The evidence base largely consisted of:

- a. Methodological frameworks describing *how* to conduct a CBA
- b. Studies demonstrating benefits of using particular methodologies or components in particular contexts
- c. Qualitative descriptions of expected impacts

This gap between available evidence and CAMBER's specific requirements necessitates a pragmatic approach to impact assessment. Partners agreed that where evidence cannot be quantified or monetised, impacts would be evaluated qualitatively within the evaluation framework to ensure comprehensive coverage of impacts across the CAMBER components, as dictated by the decision tree.

To gain a deeper understanding of well-established CBA and safety evaluation frameworks that would be particularly useful to CAMBER, live demonstrations were conducted for partners on the iRAP FSI estimation models and SafetyCube DSS methodology. Following the detailed review process and accompanying workshops, partners agreed that the CAMBER impact assessment approach would primarily draw upon methodologies and principles from iRAP (notably the FSI models), SafetyCube, and the ERSO CBA Guide. These act as a strong foundation for further development of the impact assessment approach.

Given the diversity of CAMBER components and the range of interventions to be implemented across pilot sites, partners acknowledged the need for a flexible and innovative approach to CBA where supporting evidence is available. This would enable the evaluation to capture nuanced and complex effects, such as changes in driver behaviour and road user interactions, which are not easily monetised, but remain central to assessing the impact of CAMBER solutions. The theoretical principles outlined in the following sections provide the conceptual basis for conducting CBA and FSI analysis.

4.3 THEORETICAL PRINCIPLES

Based on the agreed scope and outputs, and review of sources by partners, this section sets out the conceptual basis for CBA and FSI estimation and their application across the components and pilot sites in CAMBER.

4.3.1 COST-BENEFIT ANALYSIS (CBA)

The CAMBER project aims to improve the safety of urban and secondary roads through integrated, digitalised, and cost-effective approaches that can detect, diagnose, and respond to infrastructure and safety issues in real time. The goal of a CBA is to allow rational and transparent decision-making on adopting solutions, by providing a normative framework that guides systematic comparison of the expected costs and benefits of solutions.

In essence, a CBA is the balance of costs and benefits. Both costs and benefits are ultimately expressed in monetary terms: costs are expenditures, while benefits are savings or gains. They are conceptually of the same kind, and, in fact, are both entries in the same value scale, but with opposite signs. As noted in Section 4.1, costs associated with implementation of solutions should consider: material costs (equipment, supporting (digital) infrastructure), operational costs (resource, wages) and maintenance costs.

Whereas benefits can materialise as reductions in these costs, the primary aim of CAMBER is to improve safety. To this end, CBA will also evaluate how solutions affect safety metrics, such as the number of crashes, and how these can be attributed monetary values.

4.3.1.1 INPUTS FOR CBA

Costs

In order to perform CBA, estimates are required for one-time and recurrent material, operational and maintenance costs associated with implementation of a solution, and estimates of costs associated with safety effects. Safety effects can be expressed in terms of the number of crashes, injuries, and/or fatalities (Elvik et al., 2009). The National Highway Traffic Safety Administration distinguishes three levels of outcome (Committee on Uniform Traffic Accident Classification, 1996), namely:

- Property Damage Only (PDO)
- Injury: slight and severe (MAIS2+), and
- Fatality

Associated costs comprise of:

- Human costs H;
- Lost productivity P;
- Deployment of emergency services E;
- Medical/rehabilitation costs (short-term and long-term) M;
- Property and infrastructure damages D;
- Collective costs due to congestion, traffic delays C;
- Incident management (e.g. administrative costs, insurances)

By assigning values to these factors and combining them, it is possible to quantify the costs of fatal, injury and property-damage-only crashes. Benefits can then be quantified by contrasting the total of crash-costs, material, operational and maintenance costs in a baseline condition with the total costs after implementation of a solution - their difference is the benefit.

The main source of variation between countries is the estimation of human costs, i.e. the monetary value of loss of life or injury and the associated long-term care. This is called the value of a statistical life (VSL) and the value of a serious injury (VSI). International guidelines recommend to base this on the willingness to pay (WTP) to reduce the risk of death or injury (e.g. Blincoe et al, 2019; Wijnen et al., 2017; Bickel et al., 2006) and was estimated internationally in (Dahdah et al. 2008) as roughly: $VSL = 70 * \text{Gross Domestic Product (GDP) per capita (Current prices)}$, and the $VSI = 25\% VSL$.

In SafetyCube, crash and casualty costs were compiled for European countries, checked against international guidelines, and re-estimated where components were missing or inconsistent. This produced comparable crash and casualty costs for four severity levels: fatal, serious injury, slight injury, and damage only (the latter only for crash costs). To ensure comparability across countries and years, the value transfer method was applied. This method adjusts cost estimates from one or more “source” countries to a “target” country using correction factors based on differences in GDP per capita, price levels, and inflation rates. In this way, harmonised and up-to-date monetary values can be derived even where national WTP studies are not available. In a recent publication, the same method is applied to produce harmonised estimates for European and non-European countries (Wijnen et al., 2025). For the countries in which CAMBER pilots take place, these are based on the SafetyCube estimates – except for the Netherlands, for which new estimates exist (Schoeters et al., 2022).

Effect Sizes

Whereas costs associated with implementation of solutions can be determined or extrapolated from recorded costs at pilot site implementations, the costs (benefits) associated with safety effects must be inferred; this is done by multiplication of the estimated 'unit' costs, as described in the previous section, with (expectations on) the number of events that occur in a given timeframe, and contrasting the result between baseline, 'status-quo', and the impact of the solution.

Demonstrating effects of solutions in practice is likely to be complicated, notably by rarity of events. To illustrate: the intended pilot site North-Holland has some 14,000kms of road. In 2023, there were 87 traffic fatalities, 1,130 severe injuries, and 2,260 slight injuries. This means that for a theoretical pilot site of 50 km in length, monitored for 2.5 years, approximately 1 fatality, 10 severe injuries, and 20 slight injuries may be expected. However, observed numbers will vary due to statistical noise and covariates (e.g. vehicle throughput, road type, maximum speed).

Surrogate Safety Measures (SSM) offer alternative event types (from crashes) to inform CBA. SSM can reflect undesirable behaviours by drivers, such as maintaining short time headways (quantified by, for instance, counting the number of events where an estimated Time To Collision drops below a threshold value), or they might reflect events that could otherwise indicate unsafe situations, such as activations of vehicles' Anti-Lock Braking System (ABS). Such events occur far more frequently than actual crashes, and hence more data will be collected for a given spatiotemporal horizon, supporting impact evaluation in a shorter time frame. However, the relation of SSM to actual crashes is not always clear, and a robust approach is needed when using SSMs as a proxy for final outcomes as part of a CBA.

An alternative, and more holistic approach, is to estimate the number of fatal and injury crashes using established models which use observed risk factors and their known relationship with crashes. This is the topic of iRAP's FSI Estimation Model, which will be applied in CAMBER (see Section 4.3.2) and is described separately in Section 4.3.2.

4.3.1.2 PERFORMING CBA

Performing CBA requires contrasting the costs between a solution and a clearly defined counterfactual scenario that represents what would occur in the absence of the solution. To this end, it is necessary to record expenditures associated with implementing and performing a solution, and to quantify effects on safety indicators. The sum of the costs must then be contrasted between the baseline and intervention scenario. The choice of safety indicators will depend on the CAMBER component in question and on the nature and target mechanism of solutions.

Selecting Safety Indicators

As outlined in previous sections, direct safety indicators include traffic fatalities, (severe) injuries, and PDO crashes. These represent observable outcomes with a clear societal cost. For such indicators, monetisation can be achieved by assigning a unit cost to each event type, derived from the sum of the contributing factors listed under 'Costs' in section 4.3.1.1.

Cost definitions

The unit cost of each crash severity category can be expressed as:

$$\begin{aligned} C_{fatal} &= P + E + D + C + I + H \\ C_{injury} &= P + E + D + C + I + H + M \\ C_{PDO} &= P + E + D + C + I \end{aligned}$$

These expressions define the cost of fatal crashes, crashes resulting in injury, and the cost of a Property Damage Only crash, respectively. These costs will differ between countries and may require local calibration to pilot site conditions. For example, productivity losses depend on GDP per capita, average age at fatality, and labour market participation. Traffic delay costs depend on vehicle throughput, congestion patterns, and emergency response efficiency. Medical costs may vary according to national healthcare systems. Contextualisation is required to ensure comparability and policy relevance.

Incorporating Surrogate Safety Measures

As outlined above, where crash-based indicators are too rare to yield statistically robust effects within the observation window (as is likely in CAMBER), SSMS should be considered. To include these in a CBA, a monetisation approach must be devised. One pragmatic approximation is to estimate the empirical ratio between the frequency of SSM events and crashes, and apply this ratio to known crash cost estimates. While this introduces uncertainty, it allows preliminary valuation of safety improvements where direct crash data are sparse.

Total costs associated with selected safety indicators i can be calculated:

$$U = \sum_i (N_i C_i)$$

where:

N_i = number of events of type i (e.g. fatal, injury, PDO)

C_i = unit cost of each event type

The results must be corrected for duration of observation periods, in case these are unequal. Utilising FSI estimation models can also help to associate risk indicators with an estimated change in FSIs, which is then more easily monetisable.

CBA outputs

The main outcome of a CBA is a monetary estimate of both the benefits and the costs of a measure, solution, or programme. A measure is considered cost-effective if its benefits exceed its costs. In general, costs refer to any negative impacts associated with a measure. In many analyses (e.g. SafetyCube and other related studies), however, costs are defined as the implementation and maintenance costs, while other adverse impacts are treated as negative benefits.

The standard indicators of socio-economic performance are the NPV and the Benefit–Cost Ratio (BCR), defined as:

Net Present Value (NPV) = Present value of benefits – Present value of costs

Benefit–Cost Ratio (BCR) = Present value of benefits ÷ Present value of costs

Here, the present value of benefits would be the difference between the estimated utility U for the status quo and the intervention. A BCR greater than 1 or an NPV greater than 0 both indicate that a measure is economically efficient. Although NPV and BCR may rank measures differently, they yield the same classification of whether a measure is economically justified or not.

NPVs are typically calculated across several years and therefore should also apply discounting which reflects the time-value of money. The following equation illustrates how this can be done in a single calculation:

$$NPV = \sum_{t=0}^n \frac{C_t}{(1+r)^t}$$

where:

C_t = Net cash flow at time t (inflows minus outflows)

t = Time period

n = Total number of periods

r = discount rate (cost of capital)

The BCR tends to favour measures that offer the best value for money, even when their overall benefits are modest (e.g. because of small-scale implementation). Conversely, the NPV favours measures with large absolute benefits, even when these come at relatively high costs. Because NPVs depend on implementation scale, they are not directly comparable across measures applied at different scales. However, BCRs can be distorted if negative side effects are inconsistently treated. Therefore, all side effects—positive or negative—should be included in the numerator (benefits). For comparison across different measures, BCRs should be preferred over NPVs. In CAMBER the focus on low-cost interventions for component 5 means that associated NPVs may be small in absolute terms, and hence CBA scores can be more informative as an assessment tool (see Section 3.2.2).

Application of CBA in CAMBER

The CAMBER project applies CBA as a unifying framework for assessing the socio-economic value of innovative road safety and maintenance solutions across diverse European contexts. CBA in CAMBER is conceived as a context-sensitive yet harmonised methodology: harmonised through shared principles (e.g. using SafetyCube and iRAP cost frameworks), and context-sensitive through calibration to local economic and operational conditions using value-transfer methods and pilot-specific input data. While the core methodology remains common, its application differs by CAMBER component:

- **Component 1 – Safety-integrated maintenance systems and processes:** CBA evaluates the added value of integrating safety within maintenance operations, expressed through effects on safety, operational efficiency, and reduced lifecycle costs. Benefits include earlier detection of hazards, fewer emergency repairs, and more efficient resource allocation (for example the streamlining of site inspection procedures). A challenge for CAMBER is in monetising the benefits of combined maintenance and safety funding by adapting existing methods.
- **Component 2 – New-generation data sources:** CBA assesses efficiency gains from automation, improvements of data quality, and data driven safety improvements. Benefits are partly indirect, materialising through faster detection of defects, reduced survey costs, and enhanced decision accuracy. The challenge here is in monetising informational benefits using proxy metrics.

- **Component 3 – Digital Twins:** evaluation must consider data accuracy, reliability and system performance; with the CBA focusing on how the digital twin improves economic, safety and operational performance. Benefits may arise from reduced inspection frequency, shorter diagnostic and assessment times, and better maintenance targeting. Additional impacts may include reduced delay costs, lower asset degradation (e.g. through earlier intervention), avoided physical testing (e.g. for ADAS and other scenario analyses), and improved safety indicators when the digital twin supports faster or better informed decisions.
- **Component 4 – CCAM/ADAS performance:** CBA links infrastructure quality/Crash frequency to ADAS prevalence/reliability/performance. Safety gains are estimated via simulation or SSMs/Events from floating vehicles data, considering crash-reduction potential under improved infrastructure conditions. Costs include infrastructure adaptation, necessary ADAS/sensors, data acquisition, and maintenance of digital connectivity.
- **Component 5 – Low-cost safety interventions:** the most conventional CBA application, using established crash-cost models and before-and-after evaluations (or SSM-based proxies) to derive benefit–cost ratios. Here, results from multiple pilots will provide evidence for a European toolkit of economically efficient measures.

The evaluation framework provides much of the input data and information for CBA in CAMBER. Impact assessment (including CBA) for each component, based on the outputs from the framework, is elaborated upon in Sections 5.2 to 5.6.

To account for sources of variation between pilot sites, CBAs will be calibrated using harmonised cost factors (e.g. VSL, VSI), adjusted by GDP and price levels, following the value-transfer approach. FSI estimation models (see section 4.3.2) will be a critical input to CBA where time periods and geographical areas for assessment do not allow the use of crash data. SSMs will also be a useful tool and uncertainty ranges will capture differences in exposure, observation period, and event rarity. A multi-scenario approach (base, best, and worst case) could ensure comparability despite local constraints.

4.3.2 FSI ESTIMATION

Preventing FSIs is the ultimate ambition of the Safe System approach to road safety and the European Union has a long-term vision for zero fatalities and serious injuries by 2050 (European Commission, 2020). Therefore, as a priority outcome indicator for safety, the CAMBER project seeks to understand the potential impact of developed solutions on FSIs.

Some of the biggest challenges with estimating the impact of solutions on FSIs are typically study time frame and data sample size. Within the timescales of the CAMBER project, a rigorous before-after study with several years of collision data, and potentially matched control sites, is not feasible. Therefore, alternative methods are needed to estimate the impact of the solutions on FSIs at the pilot sites, which make use of surrogate measures or risk indicators and their links to crash risk.

To this end, CAMBER will utilise the iRAP FSI Estimation Model. This model also has the advantage that many authorities are already using it. For example, several European authorities have already undertaken network-wide assessments under the SLAIN project (Saving Lives Assessing and Improving TEN-T Road Network Safety), gaining access to iRAP Star Rating data, which is a core input to FSI estimation under the iRAP methodology.

The iRAP FSI Estimation Model provides a consistent, evidence-based method for predicting the expected number of fatal and serious injuries on a road network. It uses a combination of traffic volumes, road attribute risk and exposure to different crash types to estimate the number of FSIs likely to occur over a given period. The model builds on the large body of international crash risk research underpinning iRAP's Star Rating methodology, which classifies crash likelihood and severity for different road users based on more than 50 road attributes. By translating Star Rating risk levels and Annual Average Daily Traffic (AADT) values into expected FSI numbers, the model gives road authorities a quantitative assessment of safety performance that does not rely solely on historical crash data—which is often incomplete, unreliable, or unavailable. This enables proactive, network-wide assessment of current safety risk and future risk reduction achievable through treatment options.

The model works by combining road attribute risk factors (reflecting road attributes impact on the probability and likely severity of different crash types for different users) with traffic exposure to estimate annual FSIs. For each road segment, the Star Rating algorithm produces a risk score for each crash type appropriate to the user group (Vehicle occupant / Motorcyclist: run-off-road driver-side, run-off-road passenger-side, head-on loss-of-control, head-on overtaking, intersection, property access points, along (motorcyclist only); Bicyclist: run-off-road, intersection, and along; Pedestrian: along driver-side, along passenger-side, crossing main road, and crossing side road), which is then converted into an equivalent FSI rate using empirically derived risk curves. These values are multiplied by motor vehicle, pedestrian, bicycle, and motorcycle exposure to generate an FSI estimate per kilometre. iRAP uses this approach in its Safer Roads Investment Plans (SRIPs) to assess the cost-effectiveness of countermeasures by comparing the estimated FSIs “before” and “after” treatments over the investment life cycle. Because the model is globally standardised and does not depend on site specific police-reported crash data, it allows road managers worldwide to identify high-risk corridors, compare treatment benefits, and prioritise investments with the strongest expected reductions in deaths and serious injuries.

Application in CAMBER

The iRAP FSI methodology will be applied in several ways as part of impact assessment at pilot sites. Conducting a Star Rating assessment before solutions are implemented allows calculation of a baseline safety position. Once solutions have been implemented and data gathered to understand changes in risk indicators, a further Star Rating assessment indicates the change in safety performance and the expected FSI savings over a given time horizon. Further, through the generation of SRIPs, understanding the expected impact of different interventions can inform and prioritise implementation schedules, also providing a comparison figure for evaluation after implementation (for example, for whether individual interventions performed as expected). FSI estimation is site-specific, which will allow for comparison of the effectiveness of similar measures calibrated to the local pilot site contexts.

The FSI calculations will be aggregated by road user type to support the CAMBER KPI on assessment of safety across at least five road user groups (vehicle occupants, motorcyclists, pedestrians, bicyclists, and ADAS-equipped vehicles). FSI estimations will also be used as an input to CBA calculations (see Section 4.3.1), where the benefits associated with FSI reductions can be monetised across different European countries.

FSI calculations and the development of SRIPs have strong links with all the CAMBER components. SRIPs relate directly to component 5 (low-cost interventions), focusing on the estimation of impacts of infrastructure-related interventions. They also support component 1 (integrated safety and asset

management) as SRIPs allow for maintenance schedules to be prioritised according to safety considerations, as well as general asset degradation and renewal. FSI estimations and Star Rating scores by 100m road sections can be digitally mapped and therefore are an important component of any digital twin (component 3) solution developed for the pilot sites. New data sources (component 2) can also support easier network assessments where, for example, imagery data is automatically coded rather than relying on human data collection. New sources of dynamic data will also be used in the FSI models, providing information on vehicle speeds and traffic, for example, rather than relying on potentially poor quality or limited data from authorities.

4.3.3 ASSUMPTIONS FOR CBA AND FSI MODELLING

The application of the CBA and FSI estimation methods within CAMBER relies on several operational assumptions that ensure consistency across pilot sites and comparability of results. These assumptions are implicit in the methodological descriptions above and are stated explicitly here to support transparency and reproducibility:

- **Discount rate** – A standard social discount rate should be applied for all CBA analyses (unless national guidelines require different values), to align with commonly used rates in the European transport sector and ensure comparability across pilots.
- **Price year and monetisation values** – All monetary values (including VSL, VSI and operational costs) should be expressed in a harmonised price year. Where national estimates differ, values should be normalised using purchasing-power-adjusted conversion factors.
- **Value transfer for missing national parameters** – In cases where VSL, VSI, or intervention costs are not available for a pilot country, value-transfer methods based on EU-wide sources (such as SafetyCube) will be used. This will ensure consistent monetisation across different contexts.
- **Data quality thresholds** – Crash data, exposure data, and infrastructure attributes must meet a minimum completeness threshold to support FSI and SSM modelling. For FSI modelling the data quality thresholds are defined in the iRAP documentation (see [iRAP specification](#)).
- **Use of SSMs** – SSM-based estimates are treated as proxies for crash outcomes and are used where real crash-data sample sizes are insufficient. The conversion from SSM to expected crashes follows relationships validated in the literature and previous EU projects (such as SafetyCube). FSI estimation will use risk indicators and their links with crash risk.
- **Applicability of iRAP FSI Estimation Model** – FSI calculations assume that the iRAP model structure is appropriate for the road segments assessed in CAMBER and that any local calibration factors can be applied if needed.
- **Intervention life-cycle assumptions** – The service life of low-cost interventions (such as markings and signage) and digital components (such as software tools) will follow standardised values from the literature or national guidelines, ensuring consistency across pilots. These assumptions provide a common analytical basis for WP4 simulations and WP5 evaluations, ensuring that variations in pilot-site conditions do not compromise the comparability of impact estimates.

4.4 EUROPEAN-WIDE IMPACT ESTIMATION

This section discusses the extension of the impact assessment approach to estimating the potential socio-economic impact of CAMBER solutions if they are adopted across Europe. This wider impact evaluation is essential for informing policy decisions, supporting investment, and demonstrating the transferability of CAMBER solutions beyond the five pilot countries (Portugal, Greece, the Netherlands, Croatia, and Spain). The European-wide impact evaluation will be guided by several core principles:

1. **Harmonisation of input data across diverse contexts** – Data should be gathered from European countries pertaining to aspects important for an impact evaluation such as standardised crash costs, crash data, and other contextual factors to enable valid cross-country extrapolation.
2. **Assessment of pilot site comparability** – The pilot site context must be assessed against those in other European regions. This comparison allows for an understanding of where CAMBER results can be directly transferred, where adjustments are needed, and where impacts are likely to differ substantially.
3. **Estimation of CAMBER solution uptake across Europe** – There will be some variability in the uptake rates of CAMBER solutions across Europe due to institutional and contextual factors. As a result, the impact assessment should consider modelling different uptake scenarios.

The following sub-sections outline the data requirements, methodological approach, and key assumptions needed to extrapolate pilot-level findings to the broader European road network.

4.4.1 DATA REQUIREMENTS FOR EUROPE-WIDE EXTRAPOLATION

Extrapolating impacts from the CAMBER pilot sites to the wider European context requires access to comparable datasets, notably standardised crash costs, crashes by severity, fundamental network characteristics, and the contextual applicability of specific interventions.

Crash costs

To enable meaningful cross-country comparisons, all VSL and VSI estimates must be calculated using a consistent methodological framework and expressed in a common currency (Euros). This requires adjusting national estimates for discounting, purchasing power parity and using a common price year. The use of standardised methods is essential, as substantial variation can exist when calculating these aspects. For instance, the cost attributed to a serious injury ranges from 2.5% to 34% of the cost of a fatality depending on the country (Wijnen et al., 2019).

Where national crash data is incomplete or unavailable, the value-transfer approach recommended in SafetyCube (see Section 4.3.1.1) may be applied to estimate monetisable costs and benefits. Likewise, for countries lacking a national VSL estimate, Wijnen et al. (2025) propose harmonised value-transfer methods for high-income and low-income contexts. These approaches allow for consistent and transparent extrapolation where direct local values cannot be obtained.

Other data

Consideration of contextual and infrastructural characteristics is crucial when assessing whether pilot-site outcomes can be generalised to other European road networks. The following categories of information can support this process where locally available:

- **Traffic volume:** Exposure indicators such as AADT help contextualise the potential safety benefit.
- **Road type:** Urban vs. rural, major vs. minor, and other road classifications influence both baseline risk and the effectiveness of interventions.
- **Historical crash patterns:** Differences in the distribution of crash types — for example, regions with higher proportions of VRU crashes versus those dominated by single-vehicle car collisions affect expected outcomes.
- **Regulatory and operational environment:** Local conditions such as existing speed management, ADAS-equipped vehicle prevalence, and digital infrastructure maturity (e.g. availability of High Definition (HD) maps for digital twin applications) can influence feasibility of implementing CAMBER solutions more widely.
- **Infrastructure characteristics:** Information on road design and junction types can further refine comparability where such data exist. While these are relevant for a wider impact assessment, this data will likely be too granular for use in CAMBER.

Not all interventions tested at the pilot sites will be equally relevant or effective across every European context. A comparability assessment therefore identifies suitable road segments and contextual conditions for each CAMBER solution. Ideally, this assessment would incorporate several contextual variables such as those listed above, with appropriate weighting applied.

However, it is acknowledged that it will not be possible to acquire extensive European data during the CAMBER project. In such cases, a pragmatic approach will be taken, drawing on the most accessible and important datasets for the extrapolation calculations (e.g. available crash records and road types). Information on the number and types of crashes across Europe is the most important dataset for an estimation of effectiveness of interventions based on the evidence that will be gathered in CAMBER. Potential qualitative benefits of Europe-wide extrapolation may also be documented where quantification is constrained by available data.

4.4.2 INTERVENTION UPTAKE SCENARIOS

Even where CAMBER solutions are technically feasible, their uptake across Europe will depend on a range of external factors including local policies, funding availability, institutional capacity, stakeholder acceptance and other aspects. The Europe-wide impact evaluation will therefore model a range of uptake scenarios. To reflect varying levels of deployment, three indicative uptake scenarios are proposed:

1. **Conservative scenario (10% uptake):** Represents limited deployment, likely concentrated in early-adopter countries with strong institutional readiness.
2. **Moderate scenario (25% uptake):** Reflects broader but still selective adoption, supported by national and local policy guidance.

3. **Widespread implementation scenario (50% uptake):** Assumes widespread adoption enabled by policy mandates, harmonised standards, and sustained funding mechanisms.

Uptake rates (including baseline levels of uptake) are expected to differ by component. For example, measures within Component 5 (low-cost interventions) are likely to achieve higher penetration across Europe compared with Component 3 (DT), which requires more substantial technological and infrastructural investment. Component-specific uptake estimates can be refined during the project through stakeholder consultation, institutional readiness assessment, and evidence gathered from the pilot sites.

In addition to cross-component variation, temporal dynamics will be considered. Early-stage adoption (e.g. during the first 2-3 years of pilot deployment) may remain modest while evidence accumulates and operational frameworks mature. Higher adoption levels may be achievable after 5-8 years, once the solutions are validated, procurement pathways are clarified, and standards become embedded in European practice. The wider impact evaluation will therefore apply time-dependent scaling of uptake scenarios to reflect realistic implementation trajectories. The Europe-wide impact assessment ultimately feeds into a consolidated business case demonstrating the economic, safety, and societal value of extending CAMBER solutions beyond the five pilot countries.

4.4.3 UNCERTAINTY AND LIMITATIONS

European-wide extrapolation inevitably introduces additional layers of uncertainty beyond those present in pilot-level CBAs. These arise from several factors:

- **Transferability of results:** Outcomes observed at pilot sites may not fully generalise to all European contexts, even when adjustments for comparability are applied.
- **Data gaps and inconsistencies:** Variations in data availability and quality, particularly regarding road network characteristics, traffic exposure and crash records can limit the accuracy of estimates.
- **Variability in uptake:** Actual adoption rates of CAMBER solutions remain uncertain and will depend on factors such as national policy priorities, funding structures, institutional capacity and stakeholder acceptance.
- **Long-term dynamics:** The magnitude of safety benefits may evolve over time due to factors like vehicle fleet turnover (e.g. increasing ADAS penetration), shifting mobility behaviour or the progressive ageing of infrastructure.

Accordingly, the European-wide impact assessment within CAMBER should be viewed as an indicative estimate of potential benefits, rather than a precise forecast. The extrapolation will transparently acknowledge limitations and quantify the uncertainty associated with the results. This will ensure that subsequent interpretations and policy decisions reflect both the strengths and constraints of the underlying evidence.

5 Evaluation framework

5.1 SCOPE OF EVALUATION FRAMEWORK

The Evaluation Framework developed under Task 2.5 defines the *operational structure* and *methodological guidance* for how CAMBER's components will be tested and evaluated in controlled laboratory environments (e.g. driving simulations) and in real-world pilot sites. It provides a shared reference for all partners on the data requirements (captured in a 'Data dictionary', see Annex 3), target evaluation metrics, and testing procedures needed to plan and conduct activities such as technological development, data gathering and procurement, digital twin creation, and the testing of road safety interventions. The Evaluation Framework recognises the interconnected nature of CAMBER's components and ensures that cross-dependencies between them are systematically captured and reflected in the evaluation process. As this ensures that the framework reflects real-world complexity, it supports integrated decision-making, especially when results feed into broader impact assessments.

Rather than assessing long-term impacts, this framework focuses on how to evaluate the technical, functional, and safety performance of the CAMBER solutions during their development and demonstration stages. The evidence and harmonised metrics it produces will subsequently feed into T5.3 "Synthesis of results, evaluation and cost-benefit analysis" and T5.4 "Social and safety evaluation and impact assessment", where the wider socio-economic, safety, and policy implications will be modelled through CBA and provide a full understanding on the implications for implementing the CAMBER solutions. This approach is designed with FAIR principles in mind, making the data more useful and compatible across the project and beyond.

The purpose of the CAMBER Evaluation Framework is to:

- Establish a common methodological foundation across partners and work packages, ensuring comparability and transparency of results.
- Define data needs and metadata standards to support testing activities across all pilots and simulations.
- Set out the evaluation metrics and scoring approaches for assessing the pilot demonstrations.
- Provide structured procedures for collecting and analysing quantitative and qualitative indicators to evaluate the outcomes of each CAMBER component demonstration.

5.1.1 FRAMEWORK ARCHITECTURE

The Evaluation Framework architecture is organised into **four levels**, representing the flow from data inputs to evaluation outcomes, and corresponding directly to the tasks in WP5. The structure is not intended to capture long-term societal impacts (which are addressed in T5.4), but to operationalise *how performance is measured* within the testing and demonstration phases.

Across all components, this framework provides:

- A unified methodology: Common data definitions, testing protocols, and scoring approaches.
- Consistency and comparability: Integration of pilot results.

- Connection to the analysis of impact: Ensures the impact analysis (T5.3 and T5.4) builds on verified evaluation data.

The framework thus ensures that while each component pursues different technical objectives, their evaluations follow a shared logic and produce harmonised outputs that can be aggregated, compared, and translated into quantifiable societal benefits.

Level 1 – Inputs: Data, Parameters and Experimental Setup

This layer identifies and standardises all data inputs and contextual variables required for testing and evaluation. It specifies:

- Data types, sources, and acquisition methods (e.g. telematics, vehicle sensors, crowd-sourced data, simulation outputs).
- Definitions within a data dictionary (see Annex 3), including metadata (unit, time of measurement, update frequency, confidence level, etc.).
- The contextual and environmental conditions for laboratory and pilot tests.

This ensures consistent and traceable data collection across all partner activities. Level 1 covers everything needed before testing begins, which falls under T5.1. These are:

- Defining the experimental framework
- Specifying data requirements for laboratory and pilot tests
- Defining evaluation parameters, variables and conditions
- Aligning with WP2 KPIs and evaluation structure
- Setting up stakeholder engagement and acceptance protocols, and
- Developing pilot-specific plans and baseline definitions.

Level 2 – Processes: Testing Procedures and Analysis Methods

This layer defines the procedures and analytical methods used to conduct the evaluations, including:

- Protocols for laboratory testing (e.g. driving simulator setups, behavioural data collection).¹²
- Procedures for field evaluation in pilot sites (e.g. before/after data collection, calibration, and validation).
- Guidelines for harmonising and validating data using reference (“ground-truth”) measurements.
- Analytical methods to quantify performance based on standardised safety, maintenance, and asset indicators.

Level 2 is about how the laboratory and pilot tests are actually conducted and corresponds directly to the activities in T5.2. These include:

- Implementing and monitoring testing procedures.
- Ensuring that testing follows the experimental design developed in T5.1.
- Validating sensors, DT components, and countermeasures function as intended.

¹² Final specification of protocols for laboratory testing and field testing will be finalised in WP4 and WP5, respectively, based on specific laboratory facilities and pilot site characteristics.

- Supervising data collection methods and operational processes.
- Supporting WP3/WP4 implementation during pilot operation.
- Working with local partners to ensure consistent methodology across LLs.

By defining these methods in advance, the framework ensures that the evaluation of each CAMBER component follows consistent operational standards. A series of formal validation checkpoints (e.g. validation-gate framework) is recommended during lab and pilot implementation to verify data quality, calibration, methodological repeatability, and before–after integrity. This keeps laboratory and pilot testing disciplined and ensures only validated evidence flows to Level 3/Level 4.

Level 3 – Outputs: Indicators and Weighted Scoring System

At this level, data and observations are translated into comparable evaluation outputs. It includes:

- A catalogue of indicators and metrics.
- A weighted scoring system, combining quantitative and qualitative measures through a scaled or multi-criteria approach.¹³
- Normalisation and aggregation rules to ensure results are comparable across laboratory tests, pilot tests and components.

Level 3 covers the collection of indicators, deriving scores and producing quantitative outputs that is planned in T5.3. This includes:

- Combining laboratory/pilot results into indicators.
- Calculating weighted metrics or scoring results.
- Evaluating model performance, DT outputs, behaviour indicators.
- Quantifying cost-benefit and cost-effectiveness outputs.
- Preparing structured numerical and qualitative output sets for final evaluation.

The scoring framework provides a transparent way to assess how well each solution performs against multiple objectives, and to prioritise interventions for further development or upscaling.

Level 4 – Evaluation Results: Technical and Operational Findings

This level describes how the synthesis of test results feeds into evaluation findings for each component and the impact evaluation. It focuses on:

- Assessing the technical performance of CAMBER components (e.g. digital twin functionality, data reliability, sensor accuracy).
- Evaluating operational performance (e.g. maintenance efficiency, usability, response time).
- Capturing user-level or behavioural observations (from simulator studies or road-user feedback).

¹³ At this stage the weighting in subsequent sections is indicative, as it will only be possible to determine weighting once data have been collected.

- Defining confidence levels or uncertainty bounds for indicators before feeding into the cost-benefit modelling.

Level 4 is the bridge between empirical evidence and actionable understanding. T5.5 addresses what the results *mean* for the wider system: what has been learned, what practices are effective, and under what conditions the CAMBER solutions can be transferred or scaled. Level 4 supports T5.5 in drawing strategic, transferable conclusions for future deployment, and provides the evidence base that enables T5.5 to extract strategic insights, operational lessons, and implementation guidance across pilots.

This level also supports the impact evaluation (T5.4) by defining the harmonised data, tested metrics, and evaluation findings needed to model broader effects. This ensures that the impact assessment builds on empirical, validated evidence rather than assumptions, and that CBA and FSI estimation can be applied consistently across laboratory and pilot tests. Indicators will include confidence levels or uncertainty bounds before feeding into the cost-benefit modelling. A summary of the properties of each level and relations with tasks in WP5 is shown in Figure 6.

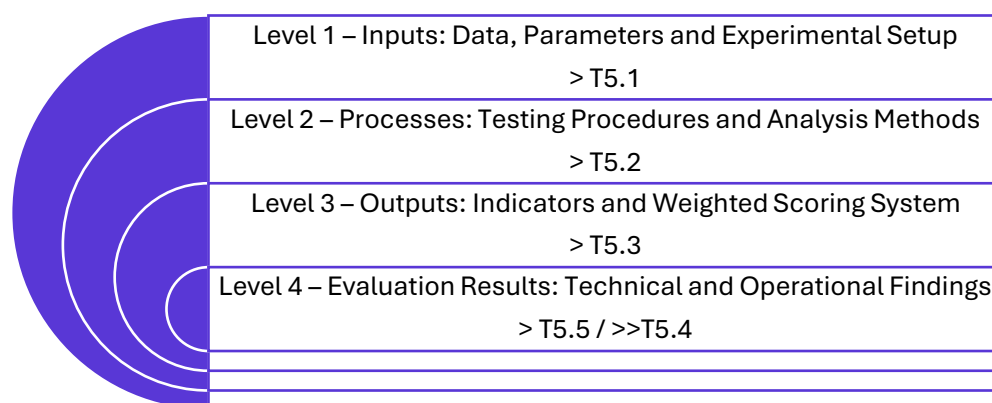


Figure 6 – Relation between four levels of the evaluation framework and tasks within WP5.

5.1.2 PILOT SITE TESTING

Evaluation of the CAMBER components will be done in the pilots. Table 4 lists a preliminary plan on which pilot area may apply to each component.¹⁴ More information is provided in Annex 5.

¹⁴ Note that the actual technical development specifications and testing plan of the road safety interventions verified in simulation environments, on-site testing and via in-vehicle safety systems will be detailed in D4.1 and the pilot experimental designs and all the activities that will take place during the trialing period at the CAMBER sites will be detailed in D5.1.

Table 4 — Preliminary plans for pilot site testing.

Location	Pilot code	Description	Key features
Trikala, Greece	TRIK1	Urban network; focusing on cycling lanes	1. Safety-Integrated Maintenance 2. New-Generation Data Sources 5. Low-Cost Safety Interventions
Trikala, Greece	TRIK2	5km (10km roundtrip) corridor connecting the city centre with the suburbs	1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 4. ADAS 5. Low-Cost Safety Interventions
Cascais, Portugal	CASC1	Bus routes M38 / M43	1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 4. ADAS 5. Low-Cost Safety Interventions
Cascais, Portugal	CASC2	Estr. Malveira, Estr. Manique, Estr. Caparide	1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 4. ADAS 5. Low-Cost Safety Interventions
Cascais, Portugal	CASC3	Whole municipal network	1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 4. ADAS
Croatia	CROA1	State road segments	1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 4. ADAS
Croatia	CROA2	Level crossings (rail-road)	1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 4. ADAS 5. Low-Cost Safety Interventions
Croatia	CROA3	Pedestrian crossings	1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 4. ADAS 5. Low-Cost Safety Interventions
Spain	SPA11	Analysis of shoulder conditions for cyclist circulation	1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 5. Low-Cost Safety Interventions

Location	Pilot code	Description	Key features
Spain	SPA12	Measurement of road superelevation on curves	<ol style="list-style-type: none"> 1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 4. ADAS 5. Low-Cost Safety Interventions
North Holland, Netherlands	NHOL1	Provincial urban and secondary roads – safety-integrated asset management testbed	<ol style="list-style-type: none"> 1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 4. ADAS 5. Low-Cost Safety Interventions
North Holland, Netherlands	NHOL2	Cycling infrastructure – provincial and municipal cycle tracks and crossings	<ol style="list-style-type: none"> 1. Safety-Integrated Maintenance 2. New-Generation Data Sources 3. Digital Twins 5. Low-Cost Safety Interventions
North Holland, Netherlands	NHOL3	High-risk curves and run-off-road locations – ROMO and probe-data monitoring	<ol style="list-style-type: none"> 2. New-Generation Data Sources 4. ADAS 5. Low-Cost Safety Interventions
North Holland, Netherlands	NHOL4	Urban roads / “School Zone 2.0” – connected-safety demonstration using IoT alerts	<ol style="list-style-type: none"> 2. New-Generation Data Sources 4. ADAS 5. Low-Cost Safety Interventions

5.2 COMPONENT 1: SAFETY-INTEGRATED MAINTENANCE SYSTEMS AND PROCESSES

5.2.1 PURPOSE

To develop and test an integrated approach that links road asset management and road safety management systems. The component explores how maintenance planning, inspection, and prioritisation processes can embed safety considerations.

5.2.2 EVALUATION FOCUS

- Assess how integration affects road network-level safety performance (e.g. changes in infrastructure risk ratings or defect-related crash likelihood).
- Measure operational efficiency, such as maintenance response time, lifecycle cost, and data interoperability.
- Determine how maintenance scheduling aligns with safety priorities (e.g. proactive rather than reactive interventions or priorities according to safety considerations, as well as general asset degradation and renewal).

5.2.3 APPLICATION OF THE EVALUATION FRAMEWORK

- **Data Dictionary:** Defines asset and safety management variables (defect types, severity, repair times, cost, crash linkage).
- **Testing Procedures:** Evaluate integration through simulation and pilot trials of data exchange workflows.
- **Indicators:** Multi-criteria evaluation covering safety, operational efficiency, and asset performance.
- **Weighted Scoring:** Combines technical, economic, and safety metrics to rate the effectiveness of integration approaches.
- **Outputs to Impact Assessment:** Provides evidence for CBA comparing integrated versus conventional maintenance systems.

5.2.3.1 DATA DICTIONARY

The data dictionary for this component defines the variables needed to assess how safety management can be embedded within maintenance systems. Key parameters include defect type and severity, repair times, inspection frequency, cost of intervention, and any linkage to recorded crashes or iRAP risk attributes.

Metadata entries specify units of measurement (e.g. IRI (mm/km), rut depth (mm), or inspection intervals), data sources (maintenance records, iRAP datasets, telematics), and collection methods (audits, inspections, surveys, or automated probes). These entries ensure comparability between pilot sites and enable cross-referencing with the wider Evaluation Framework's indicator catalogue.

5.2.3.2 TESTING PROCEDURES

Testing focuses on evaluating the degree of integration between safety and asset management processes in both laboratory and pilot environments. Procedures include:

- Audits of maintenance records to determine whether safety indicators are recorded during inspections.
- System reviews of planning processes to check whether risk-based prioritisation is applied.
- Before–after analyses and simulation exercises to quantify safety improvements arising from maintenance actions.
- Qualitative reviews and stakeholder interviews with maintenance planners and road authorities to understand operational barriers and cooperation between departments.
- Quantitative assessment of the change in the diagnostic period for risk sites, shifting from crash frequency-based to event frequency-based safety analysis.
- Cost comparisons between specialised surveys (e.g. IRI, Ecodyn3, or traffic counters) and new data-sourced indicators. Evaluation of minimum observation periods for comparable accuracy, and assessment of change in diagnostic frequency, shifting from crash frequency-based to event frequency-based safety analysis.

Each pilot will verify that performance metrics developed in CAMBER are embedded into existing asset management workflows and trigger maintenance actions when safety thresholds are reached.

5.2.3.3 INDICATORS

Evaluation indicators cover three main dimensions:

1. **Safety performance:** reduction in identified risks, improved visibility, or lower crash likelihood based on iRAP and telematics data.
2. **Operational efficiency:** timeliness of maintenance and safety intervention, cost of interventions, and reduction in duplicated inspections.
3. **Asset performance:** life-cycle improvements and cost–benefit of linking safety and maintenance decisions.

Qualitative indicators such as cooperation between safety and maintenance departments, intangible costs, and usability of new metrics complement these quantitative measures. All indicators are linked to entries in the data dictionary to maintain consistency across pilots.

5.2.3.4 WEIGHTED SCORING

Results are aggregated using a multi-criteria weighted scoring system that combines safety, technical, and economic performance. Scores reflect the relative contribution of each dimension to the overall effectiveness of the integrated system. For example, weighting may emphasise:

- Safety improvement (40%),
- Operational efficiency (30%)
- Cost-effectiveness (30%)

The scoring enables comparison across different environments and highlights where integrated approaches deliver the greatest benefit.

5.2.3.5 OUTPUTS TO IMPACT ASSESSMENT

The evaluation outcomes for this component will feed directly into the respective tasks in WP5. Quantified improvements in safety performance, including the impact of indirect benefits (Byaruhanga & Evdorides, 2024), asset condition, and maintenance efficiency will be used as evidence for cost–benefit analysis (CBA) and FSI reduction modelling. An approach will be developed to value the benefits of combined safety and maintenance funding, available for road administrations willing to progress into higher levels of integration. Overall, this will be adapted from existing methods (e.g. Thiessen et al., 2017), but will require customisation to each road administration, depending on available data.

The results will demonstrate whether the harmonisation of safety and asset management systems offers measurable socio-economic advantages over conventional maintenance practices, providing a validated foundation for scaling these methods to the European secondary road network.

5.3 COMPONENT 2: NEW-GENERATION DATA SOURCES

5.3.1 PURPOSE

To identify, test, and validate **emerging and dynamic data sources** (e.g. telematics, connected vehicles, mobile sensors, drones) for road safety and maintenance applications.

5.3.2 EVALUATION FOCUS

- Accuracy and reliability of novel data collection compared to traditional surveys.
- Coverage and update frequency (can new data sources fill existing gaps?)
- Feasibility and scalability for operational use by road authorities.
- Added value to existing safety models and performance indicators.

5.3.3 APPLICATION OF THE EVALUATION FRAMEWORK

- **Data Dictionary:** Defines metadata (sampling rate, spatial resolution, confidence intervals).
- **Procedures:** Establish validation and cross-comparison protocols using reference datasets.
- **Indicators:** Data quality indicators (completeness, timeliness, spatial precision), plus derived performance measures.
- **Weighted Scoring:** Ranks data sources by quality, cost, and potential for integration.
- **Outputs to Impact Assessment:** Quantifies efficiency gains, potential data-driven safety improvements, and cost reductions for future adoption.

5.3.3.1 DATA DICTIONARY

The data dictionary for this component defines the variables, metadata, and quality indicators used to validate and integrate diverse data streams—vehicle, sensor, satellite, and infrastructure-based. Key fields include data source type, acquisition method, spatial and temporal resolution, update frequency, and associated uncertainty or confidence levels.

Metadata capture differences between traditional and new data sources, supporting comparative analysis of coverage, availability, resolution, and cost. Each dataset is benchmarked against “ground-truth” reference data to ensure quality and traceability across all laboratory and pilot testing.

5.3.3.2 TESTING PROCEDURES

Testing focuses on verifying the accuracy, reliability, and operational usefulness of new data sources and their integration into asset and safety management workflows.

Procedures include:

- Comparative analyses between new and traditional data for equivalent metrics in the same geographical region.
- Validation of data frequency, resolution, and coverage, determining whether new sources provide higher update rates or finer granularity.
- Ground-truth benchmarking, comparing detection of defects or hazards using new data versus reference measurements (e.g. AIT RoadLab).
- Integration testing to verify digital connectivity between vehicles, infrastructure, and management systems, and to assess levels of automation in data collection.
- Reliability testing for completeness, consistency, and accuracy across different collection methods and pilot sites.

These tests demonstrate how new data sources can enhance automation, enable near-real-time monitoring, and support evidence-based maintenance and safety decisions.

5.3.3.3 INDICATORS

The evaluation indicators for this component address both data quality and system performance:

1. **Cost efficiency:** relative data acquisition cost per kilometre or per parameter measured.
2. **Update frequency:** temporal resolution of data streams compared with legacy datasets.
3. **Availability and coverage:** proportion of network or assets with valid, continuous data.
4. **Resolution and repeatability:** spatial precision and stability of repeated measurements.
5. **Integration capability:** success of linking vehicle, sensor, and satellite data into digital twins, safety assessments, and/or asset systems.
6. **Metric improvement:** extent to which inclusion of new data improves accuracy and sensitivity of safety or asset metrics.
7. **Automation level:** share of data acquisition and processing performed automatically.

All indicators are linked to data dictionary entries defining units, validation methods, and responsible partners.

5.3.3.4 WEIGHTED SCORING

Evaluation results are aggregated using a multi-criteria weighted scoring system to rank new data sources by quality, cost, coverage, and operational benefit. Example weighting might prioritise:

- Data accuracy and reliability (40%)
- Coverage and update frequency (30%)
- Cost-effectiveness and automation potential (30%)

This structured scoring enables consistent comparison of different data types and supports decision-making about which sources to incorporate into future monitoring systems.

5.3.3.5 OUTPUTS TO IMPACT ASSESSMENT

The evaluation outcomes will directly inform the respective tasks in WP5 by providing validated evidence of how new data sources enhance monitoring, reduce costs, and improve safety and maintenance metrics. Results including cost-benefit comparisons, accuracy improvements, and time-to-detection analyses will feed into CAMBER's broader cost-benefit and FSI reduction modelling. The findings will demonstrate the potential for large-scale adoption of dynamic and automated data systems across Europe's secondary rural and urban road networks, highlighting both technical feasibility and socio-economic return.

5.4 COMPONENT 3: DIGITAL TWINS

This section outlines the evaluation framework which will be used in CAMBER Task 4.4 to support the Digital Twin developments across pilots, Task 5.4 to evaluate the capacity of digital twins deployed in pilots to support road asset and safety management and Task 4.5 to inform the Digital Twin roadmap. Component 3 focuses on the technical performance, fidelity, simulation and forecasting capacity, resilience and added value of digital twins compared with traditional approaches. The framework draws directly on the digital twin taxonomy reported in CAMBER Deliverable 2.1, ensuring that maturity levels (representation fidelity, data synchronisation, simulation functionality, predictive capability, and scenario testing) are consistently assessed across the pilot contexts.

5.4.1 PURPOSE

To assess the efficacy of digital twin models designed for urban and/or secondary road networks, supporting enhancement of monitoring, decision support and predictive management. Specifically, it is the framework to measure:

- Fidelity of the digital twin's representation of assets or conditions
- Capacity to simulate asset behaviour, such as deterioration patterns or traffic-related risks
- Capacity to forecast future conditions and safety-critical situations
- Ability to support scenario testing for maintenance and safety planning
- Operational reliability of the real-time data ecosystem
- The value added to managerial processes, including decision timelines, cost reductions, and improved safety indicators.

The evaluation framework should ensure comparability across laboratory and pilot testing through normalised indicators and clear quality thresholds for data, performance, and usability.

5.4.2 EVALUATION FOCUS

The evaluation framework for this Component comprehensively addresses key dimensions essential for the success of the digital twins addressed in CAMBER, including functionality, interoperability, analytical capability, and usability.

- **Functionality:** High model fidelity through accurate real-world replication and continuous data updates; validity of simulation and prediction capabilities for monitoring, decision making or control.
- **Interoperability:** Smooth integration with existing systems and compliance with data standards; validates efficient data exchange and compatibility across systems.
- **Analytical capability:** Enables scenario testing, decision support, and safety risk visualization; confirms that the model is useful and effective in managing complex situations.
- **Usability:** Intuitive dashboards and interfaces designed for authorities and researchers; validates accessibility and effective user interaction

This framework is informed by the digital twin taxonomy, detailed in CAMBER Deliverable 2.1, defining capabilities mainly through Functional Scope (encompassing simulation & analysis, data integration, visualization, and decision support & control) and Application Scale (covering component, asset, system, and process twin levels). The evaluation focus areas assess whether functional requirements and application scale have been achieved, enabling consistent assessment of maturity levels across pilot contexts including fidelity, synchronisation, simulation, prediction, and testing.

5.4.3 APPLICATION OF THE EVALUATION FRAMEWORK

- **Data Dictionary** ensures coherence, data quality, interoperability, and alignment.
- **Procedures** define how technical validation, simulation validation, and user-centred testing are conducted.
- **Indicators** provide measurable, traceable evidence of system performance, usability, and impact.
- **Weighted Scoring** aggregates results into comparable performance profiles across pilots.

- **Outputs to Impact Assessment** translate evaluation findings into quantifiable and qualitative evidence for Task 5.4, including CBA, safety modelling, and socioeconomic impact estimation.

5.4.3.1 DATA DICTIONARY

The data dictionary for this component defines all datasets supporting the digital twin data ecosystem, covering both real-time and historical records. It specifies:

- **Data types:** asset geometry, safety, environmental parameters (temperature, moisture, heat stress).
- **Data attributes:** update frequency, transmission latency, spatial resolution.
- **Data source:** mobile sensor, infrastructure sensor, vehicle sensor, satellite, or asset database.
- **Metadata:** integration method with the twin environment (API, file transfer, or live stream); partner responsible and quality assurance role; validation method (cross-checking, ground truth, sensor diagnostics); dependencies across datasets; performance parameters (for example, system uptime $\geq 95\%$, transmission latency $< 2\text{-}5$ seconds for real time data).
- **Taxonomy alignment:** each dataset is mapped to the taxonomy dimension it supports.

These structured definitions ensure the consistent integration, validation and comparability of digital twins across different pilot conditions and technical maturities with diverse urban and/or secondary road contexts.

5.4.3.2 TESTING PROCEDURES

Testing procedures assess both the technical robustness of the digital twin and its usability as a decision-support tool. Procedures are grouped into two categories.

A. Technical validation procedures

- **Integration and connectivity testing** to confirm stable links with assets, sensors, vehicle systems, and data platforms, with pass/fail thresholds based on latency, packet loss, and synchronisation.
- **Performance monitoring** for assessing latency, refresh rates, uptime, and error frequency within real pilot conditions.
- **Forecasting validation** using back-testing to measure predictive accuracy (Mean Absolute Percentage Error - MAPE, Root Mean Square Error - RMSE, deviation from ground truth).
- **Resilience testing** evaluating behaviour under degraded data conditions, sensor gaps, or high-load scenarios.

B. User-centred validation procedures

- **Usability studies** with end users (road managers, engineers) to assess accessibility, interface clarity, and potential integration into existing workflows.
- **Decision support testing** evaluating how quickly and confidently end users (engineers, road managers) can interpret outputs and act upon them.
- **Operational case studies** documenting real instances in which the digital twin supported or accelerated maintenance or safety interventions.

These procedures ensure that performance claims are evidence based, replicable and aligned with evaluation expectations.

5.4.3.3 INDICATORS

Indicators are used to assess both system performance and its contribution to operational and safety outcomes:

1. **Connectivity performance:** latency, uptime, error rate, and system stability.
Threshold: uptime \geq 95%, latency $<$ 5 sec for safety-critical data, refresh stability: \pm 10% of nominal rate
2. **Data accuracy and reliability:** consistency between the digital twin metrics and verified ground-truth data (MAPE/RMSE).
Target: accuracy \geq 85%. Scenario specific tolerances may also be applied (such as \pm 10% geometric deviation, \pm 2km/h speed deviation)
3. **User interaction and uptake:** frequency of use, session duration, task completion rate, user satisfaction scores. Scenario specific metrics may also be applied (such as number of ADAS readiness test runs for ADAS validation, daily scenario configurations by operators for traffic related scenarios, number of maintenance planning sessions supported for asset management)
Target: 4/5 usability score
4. **Decision-support effectiveness:** time reduction in decision-making, number of decisions supported by digital twin insights.
Target: \geq 15% reduction in response time compared to baseline
5. **Safety and asset performance improvements:** improvements in risk scores, reduced maintenance response times, improved network condition indicators, linked to twin-based decisions. It may capture how scenario-based insights improve risk mitigation (e.g. what if or simulation).
Measured monthly.
6. **Sustainability and efficiency:** reductions in emergency interventions, travel time, emissions, lifecycle costs. Evaluates resource, cost benefits arising from using digital twin instead of manual or physical processes.
Inputs to CBA. Must specify units for benefits (e.g. €, time, km, failures prevented)

Each indicator is linked to its dataset, validation process, and measurement units in the data dictionary (see Annex 3).

5.4.3.4 WEIGHTED SCORING

A multi-criteria scoring approach is used to compare digital twin performance across pilots, with normalisation to account for contextual differences (for example, traffic levels, climate, or network type), which combines system performance, usability, and impact metrics. Indicative weighting may be assigned as follows:

- **Technical reliability and connectivity (35%)**
Justification: A digital twin must demonstrate stable and accurate functioning before generating value.
- **Usability and decision-support effectiveness (35%)**
Justification: Adoption and organisational integration determine real-world impact.
- **Operational and safety impact (30%)**
Justification: Tangible improvements in maintenance and safety are the core expected values.

Methodological notes: Scores should be aggregated using a weighted linear combination, with a sensitivity analysis assessing the robustness of conclusions against variations in weighting. Context normalisation may also be applied to adjust for differences across pilot environments, ensuring fair comparability. This approach enables a clear cross-pilot evaluation, highlighting where digital twins deliver the strongest performance gains, whether in improved maintenance planning, ADAS readiness, or safety management, and provides a robust foundation for benchmarking different digital twin configurations and levels of integration.

5.4.3.5 OUTPUTS TO IMPACT ASSESSMENT

Component 3 evaluation framework will be directly fed into Tasks 4.4, 4.5, and 5.4. The following data flows apply:

A. Quantitative inputs to CBA and FSI modelling

- Reduced maintenance response time, leading to operational cost reductions
- Enhanced risk prediction accuracy, allowing for adjustments in expected crash likelihood
- Fewer emergency repairs, resulting in lifecycle cost savings
- Improved decision timelines, affecting maintenance frequency and timing
- Refined asset-condition forecasts, enabling more efficient budgeting

B. Qualitative inputs

- User adoption and organisational readiness
- Perceived reliability and trust in digital twin tools
- Capacity for integration with existing planning systems
- Replicability and scalability assessments across EU contexts

The results will demonstrate the socioeconomic value of applying digital twins to secondary and/or urban road networks, providing evidence and guiding recommendations for scaling the approach across Europe.

A clear way to strengthen the link between technical maturity and expected benefits is to reference graduated levels of digital twin development, consistent with the taxonomy introduced in Deliverable 2.1. For CAMBER, these maturity levels can be summarised as:

- **Level 1 – Visual Model** is where the DT provides a static or periodically updated digital representation of assets and supports improved situational awareness and baseline documentation,
- **Level 2 – Data-Linked Monitoring** where real-time or high-frequency synchronisation enables continuous condition monitoring and diagnostic insight, and enables timely detection of asset defects, emerging risks, and maintenance needs, and
- **Level 3 – Predictive and Decision-Support Twin** where simulation, forecasting, and scenario analysis support proactive maintenance and safety decision-making, and is capable of predictive maintenance, risk forecasting, and rapid decision support that could materially reduce lifecycle costs and improve safety outcomes.

These levels clarify how increasing digital twin maturity unlocks progressively greater operational and safety benefits. Framing results in this way provides a structured foundation for the **monetisation of**

benefits under T5.3, where each level can be associated with specific cost-reduction mechanisms (e.g. avoided emergency repairs, reduced inspection cycles, improved risk mitigation) and translated into quantifiable socio-economic value for the cost–benefit analysis.

5.5 COMPONENT 4: ADAS PERFORMANCE

5.5.1 PURPOSE

To evaluate Advanced Driver-Assistance Systems (ADAS) in the context of secondary road conditions, identifying gaps and potential improvements.

5.5.2 EVALUATION FOCUS

- Performance consistency of key ADAS functions (e.g. lane-keeping, speed assistance) on non-motorway roads.
- Influence of road infrastructure features (signage, markings, geometry) on ADAS reliability.
- Driver interaction and behavioural adaptation under simulated and real-world conditions.

5.5.3 APPLICATION OF THE EVALUATION FRAMEWORK

- **Data Dictionary:** Standardises ADAS performance variables (trigger rate, false positives, disengagements).
- **Procedures:** Lab testing using driving simulators; controlled field trials in pilots.
- **Indicators:** Detection accuracy, safety margin improvement, driver workload.
- **Weighted Scoring:** Rates system robustness, safety contribution, and user acceptance.
- **Outputs to Impact Assessment:** Provides quantified benefits (FSI reduction potential) and guidance for road-vehicle interface design on secondary networks.

5.5.3.1 DATA DICTIONARY

The data dictionary for this component defines the variables and metadata required to evaluate the interaction between road infrastructure condition and the performance of Advanced Driver Assistance Systems (ADAS). Key entries include:

- Vehicle and infrastructure sensor data (trajectory data, CAN bus logs, external sensor feeds).
- Simulation parameters (scenario type, environmental conditions, system activation state).
- Performance metrics such as lane detection accuracy, speed assist reliability, and conflict indicators (for e.g. PET, TTC).
- Infrastructure attributes (surface quality, signage, marking reflectivity, C-ITS equipment).

Each dataset is characterised by its type (internal/external), frequency, spatial resolution, and calibration method. The dictionary ensures alignment between vehicle-based and infrastructure-based data for consistent ADAS evaluation across laboratory and pilot testing.

5.5.3.2 TESTING PROCEDURES

Testing focuses on assessing ADAS functionality under varying road and infrastructure conditions to understand how infrastructure quality affects system reliability and safety. Procedures include:

- Sensor-fusion analysis combining internal (vehicle) and external (infrastructure, telematics) data streams to identify safety events and performance differences.
- Simulation campaigns to test ADAS accuracy and responsiveness under controlled variations in road condition, markings, and geometry.
- Pilot-based testing to review use cases where ADAS-related data (e.g. lane detection errors or speed assist reliability) informed maintenance prioritisation or inspection scheduling.
- Integration analysis of ADAS-derived insights into maintenance workflows and intervention selection.
- Before–after analyses to quantify road condition and safety improvements resulting from ADAS-informed maintenance.
- Usability assessments with road managers to evaluate how ADAS data is incorporated into planning and decision-making.

These procedures collectively demonstrate how ADAS data can serve both as a performance indicator and as a maintenance trigger in asset management systems.

5.5.3.3 INDICATORS

Indicators are linked to the data dictionary to ensure traceability between vehicle, infrastructure, and simulation data sources. The evaluation indicators for this component are grouped into five domains:

1. **ADAS Performance:** Accuracy, reliability, and stability of ADAS functions (lane keeping, speed assist, hazard detection) across test conditions.
2. **Infrastructure Quality:** Road surface, signage, and marking condition, measured through physical inspection or derived from ADAS sensor data.
3. **System Integration:** Degree to which ADAS outputs are used in maintenance decision tools and low-cost intervention prioritisation.
4. **Operational Efficiency:** Reduction in inspection time, faster detection of defects, and improved targeting of maintenance actions using ADAS-informed workflows.
5. **Safety Impact:** Improvements in Star Ratings, reduced conflict metrics, or lower FSI risk following ADAS-informed interventions.

For CAMBER it can be concluded that, either specific crash data and road condition data for ADAS equipped vehicles (or share of ADAS equipped vehicles in the respective local area) can be obtained or the immediate option of impact assessment for ADAS is through simulation. CAMBER work packages 4 and 5 could evaluate the feasibility of appropriate simulation environments and virtual crashes could be used for impact assessment. An alternative using floating vehicles data could be to use event data. As safety critical events are defined and evaluated in the project, the safety events of ADAS equipped vehicles, if specified, could allow for an actual real-world events based CBA of ADAS.

5.5.3.4 WEIGHTED SCORING

A multi-criteria weighted scoring system is applied to combine technical, operational, and safety dimensions of ADAS performance. Example weighting:

- Technical accuracy and reliability (40%)
- Infrastructure influence and integration (30%)
- Safety and operational benefit (30%)

This approach allows results from laboratory simulations and real-world pilots to be compared and aggregated. It highlights how infrastructure quality influences ADAS effectiveness and where targeted maintenance can most improve system reliability.

5.5.3.5 OUTPUTS TO IMPACT ASSESSMENT

The evaluation results from this component feed directly into Task 2.4 (Impact Assessment), providing data to quantify the safety and economic benefits of maintaining ADAS-compatible infrastructure. Key outputs include:

- Quantitative data on ADAS reliability improvements and their link to infrastructure condition.
- Evidence of maintenance efficiency gains where ADAS data guided interventions.
- Before–after performance results showing measurable safety benefits.

These outputs will support cost–benefit analyses and modelled FSI reduction estimates, demonstrating how maintaining machine-readable roads enhances both human and automated vehicle safety performance across Europe’s secondary road network.

5.6 COMPONENT 5: LOW-COST SAFETY INTERVENTIONS

5.6.1 PURPOSE

To test cost-effective physical and behavioural road safety measures, such as signage, markings, traffic-calming elements, and low-cost infrastructure modifications.

5.6.2 EVALUATION FOCUS

- **Safety effectiveness** as judged by change in Star Rating or surrogate safety measures (e.g. speed, conflicts, compliance) in driving simulator studies.
- **Implementation practicality** including cost, ease of deployment, local acceptance.
- **Environmental and social effects** such as comfort, accessibility, noise, emissions.

5.6.3 APPLICATION OF THE EVALUATION FRAMEWORK

- **Data Dictionary:** Specifies pre- and post-intervention data types (e.g. speeds, flows, near-misses).
- **Procedures:** Defines before–during–after monitoring, control site comparison, and data validation.
- **Indicators:** Quantitative (e.g. speed reduction, FSI risk decrease) and qualitative (user perception, comfort).
- **Weighted Scoring:** Combines safety, cost, comfort, and accessibility dimensions to rank intervention performance.
- **Outputs to Impact Assessment:** Supplies input for detailed CBA and extrapolation of FSI and cost savings in T5.3.

5.6.3.1 DATA DICTIONARY

The data dictionary for this component defines the variables and metadata related to the development, implementation, and evaluation of simple, scalable, and economically feasible road infrastructure treatments. Key entries include:

- Intervention type and description (treatment category, purpose, and installation details).
- Location attributes (road type, traffic composition, baseline risk rating).
- Implementation parameters (cost, duration, required maintenance, and replicability factors).
- Performance indicators such as changes in user behaviour (speed, positioning), surrogate safety measures (near-miss frequency), and cost–benefit ratios.

Each dataset includes metadata on measurement methods (e.g. observational, telematics, survey), collection frequency (before–after), and data owners (pilot authorities, contractors, evaluation partners). This structure ensures comparability of low-cost intervention outcomes across pilot sites and supports transferability analysis.

5.6.3.2 TESTING PROCEDURES

Testing focuses on assessing the effectiveness, feasibility, and scalability of low-cost infrastructure interventions at both pilot and cross-site levels. Procedures include:

- Simulation and before–after analyses to assess how interventions affect user behaviour, safety outcomes, and cost efficiency.
- Pilot implementation studies at selected sites to measure improvements in speed management, visibility, and conflict reduction.
- Cross-checking with crash risk maps and predictive models (e.g. iRAP Star Ratings, heatmaps) to confirm alignment between observed and modelled safety benefits.
- Consultations with pilot sites and authorities to validate intervention selection, feasibility, and maintenance implications.
- Comparative analysis of intervention types across road environments to determine replicability and transferability.
- Stakeholder surveys and practitioner interviews to gather qualitative insights on practicality, barriers, and willingness to adopt.

Testing demonstrates how low-cost measures can deliver measurable improvements in safety and maintenance efficiency with limited financial and administrative resources.

5.6.3.3 INDICATORS

Indicators for evaluating low-cost interventions address performance, cost-effectiveness, and scalability:

1. **Safety performance:** Changes in crash proxies (e.g. near-miss frequency or Star Ratings).
2. **User behaviour:** For example, speed profiles, lane discipline, overtaking distance, etc.
3. **Operational efficiency:** Implementation and maintenance cost per kilometre or treated site.
4. **Transferability and scalability:** Number of successful demonstrations and ability to replicate interventions under similar conditions.
5. **Stakeholder acceptance:** Qualitative feedback from road authorities, contractors, and users.

Each indicator links to data entries in the dictionary, ensuring traceability between field data, simulation results, and cost analysis outputs.

5.6.3.4 WEIGHTED SCORING

A multi-criteria weighted scoring system aggregates results across safety, cost, and scalability dimensions. Example weighting:

- Safety benefit and user behaviour improvement (40%)
- Cost-effectiveness and ease of implementation (30%)
- Replicability and long-term sustainability (30%)

Scores enable comparison of intervention types and prioritisation of those with the highest return on investment, supporting the creation of a Toolkit of Low-Cost Interventions for wider use.

5.6.3.5 OUTPUTS TO IMPACT ASSESSMENT

The evaluation results generated under Component 5 will feed directly into impact assessment through WP5, supplying both the quantitative and qualitative evidence required. As low-cost safety interventions often rely on short deployment times and readily observable behavioural responses, this component delivers some of the clearest and most transferable evidence within the CAMBER framework.

The outputs of Component 5 can possibly encompass several elements:

1. The evaluation produces quantitative performance metrics derived from before-and-after evaluations, which can encompass changes in speed profiles, surrogate safety indicators, and overtaking distances, among others. These metrics enable the iRAP FSI estimation reduction calculations, which serve as direct inputs into CBA monetisation models.
2. The evaluation generates real-world cost and implementation evidence, including installation cost and maintenance requirements. These data support the estimation of intervention cost-effectiveness as required for BCR and NPV calculations.
3. The evaluation can be used to provide operational evidence on installation constraints and operational disruptions. These outputs support assessment of transferability across different road environments and are essential for extrapolating pilot results to European-wide scenarios in WP5.
4. The evaluation can be used to capture qualitative findings on feasibility, local acceptance, user perception, and organisational readiness. These insights can be gathered from interviews, surveys, and stakeholder feedback. They can be used to add context to the qualitative evaluations and help clarify the practical conditions under which interventions can be successfully adopted.
5. Component 5 can contribute to deliver toolkit outputs that synthesise the comparative performance of interventions into a structured set of recommended measures. This can include a ranked list of effective, affordable, and easily deployable low-cost safety interventions, supported by quantitative evidence from pilots and validated by expert judgement. These materials will support the modelling of FSI reduction potential at scale and help WP4 and WP5 select solutions for testing and deployment.

Together these outputs will demonstrate the safety, operational, and economic value of low-cost safety interventions, providing road agencies with a transparent and evidence-based foundation for prioritising

scalable improvements on urban and secondary roads. They ensure that the impact assessment is based on empirical performance data rather than assumptions, enabling credible estimation of crash reductions, cost savings, and long-term benefits for European road networks.

5.7 SUMMARY

Table 5 links each component's KPIs to the monetisable benefit categories: safety improvements, operational efficiency, data quality enhancement, and lifecycle cost reduction. This clarifies how the technical evidence from laboratory and pilot evaluations translates into economic value, ensuring a clear line of sight from measured performance to cost–benefit outcomes. It also supports consistent comparison across components and provides a coherent basis for aggregating benefits in the final CBA.

Table 5 — Overview of links between components, key KPIs, and monetizable benefits.

Component	Key KPIs	Monetisable benefit	Why
Component 1: Safety-Integrated Maintenance	<ul style="list-style-type: none"> Safety performance (risk reduction, improved visibility, lower crash likelihood) Operational efficiency (repair times, inspection frequency, response time) Asset condition improvement Cooperation/usability indicators 	<ul style="list-style-type: none"> Safety improvements Operational efficiency Lifecycle cost reduction 	<ul style="list-style-type: none"> Reduced crash likelihood → FSI reduction that feeds CBA Faster and better-targeted maintenance → fewer disruptions, less downtime Improved asset lifespan → long-term cost savings Reduced duplication of inspections
Component 2: New-Generation Data Sources	<ul style="list-style-type: none"> Accuracy, reliability, completeness Coverage and update frequency Cost per unit of data Automation and repeatability Integration capability with asset/safety systems 	<ul style="list-style-type: none"> Data quality enhancement Operational efficiency Safety improvements 	<ul style="list-style-type: none"> Higher-quality data reduces errors and improves targeting of interventions Automation lowers cost of collection and shortens diagnostic cycles Greater accuracy improves risk detection, informing safer decisions
Component 3: Digital Twins	<ul style="list-style-type: none"> Connectivity and uptime Predictive accuracy (MAPE, RMSE) User interaction/usability Decision-support effectiveness (time savings) Safety and asset performance improvements (risk score reductions, maintenance response time) 	<ul style="list-style-type: none"> Operational efficiency Safety improvements Data quality enhancement Lifecycle cost reduction 	<ul style="list-style-type: none"> Real-time monitoring & prediction reduce emergency repair costs Faster decision-making reduces delays and resource waste Improved safety forecasting enables targeted interventions Higher-fidelity data reduces uncertainty in CBA modelling

Component	Key KPIs	Monetisable benefit	Why
	<ul style="list-style-type: none"> Sustainability/efficiency indicators 		
Component 4: CCAM/ADAS Performance	<ul style="list-style-type: none"> ADAS accuracy, reliability, stability Infrastructure quality impacts on ADAS (markings, signage, geometry) Integration of ADAS insights into maintenance Operational efficiency (targeted inspections) Safety impact (Star Rating improvement, conflict reduction) 	<ul style="list-style-type: none"> Safety improvements Operational efficiency Data quality enhancement 	<ul style="list-style-type: none"> Better ADAS operations reduce crash risk ADAS-generated diagnostics optimise maintenance schedules Using ADAS data reduces need for manual inspections
Component 5: Low-Cost Safety Interventions	<ul style="list-style-type: none"> Safety performance (speed, conflicts, overtaking distance, Star Rating) User behaviour indicators Implementation and maintenance cost Transferability & scalability Stakeholder acceptance & feasibility 	<ul style="list-style-type: none"> Safety improvements Lifecycle cost reduction Operational efficiency 	<ul style="list-style-type: none"> Rapid and affordable safety improvements lower FSI risk Low-cost treatments provide high BCR in CBA Minimal installation/maintenance demands → scalable savings

5.7.1 KEY ASSUMPTIONS

The core assumptions used as part of the evaluation plan are provided here:

- Pilot sites will provide the minimum required localised crash and exposure data for surrogate safety measures (SSM) and fatal and serious injury (FSI) estimation.
- The evaluation measures will be completed to the required level of accuracy
- SSMs and iRAP FSI estimation models will be sufficient to estimate safety impacts within project timescales (since long before-after crash datasets are infeasible).

6 Conclusions and implications for CAMBER

This deliverable has brought together three key elements from WP2. First, a set of CAMBER solutions has been identified (Sections 2 and 3), offering opportunities for laboratory testing and pilot site demonstration. A subset of the identified solutions will be evaluated in a laboratory setting (WP4). The outcome of this evaluation will inform which solutions will eventually be implemented in pilot site demonstrations (WP5). The set of solutions comprises 16 non-intervention solutions focusing on CAMBER components 1-4 (i.e. integration of RAM and RSM, new-generation data sources, digital twins, ADAS performance), with the potential of integrating RAM and RSM at most hierarchical levels (strategic, tactical, operational) identified in a dedicated integration framework. Furthermore, 30 solutions (or: interventions) relating to CAMBER component 5 (i.e. low-cost safety solutions) were identified through co-creation with pilot sites. As a second key element, the approach to impact assessment to be applied in WP5 has been prepared (Section 4), both for pilot site assessment, as well as wider European-scale extrapolation. The theoretical principles outlined followed from extensive literature review of existing methods to cost-benefit analysis. Third, an evaluation framework has been developed (Section 5), which will guide implementation of solutions at the pilot sites. The architecture of the framework consists of a evaluation purpose and focus, data dictionary, testing procedures, indicators, weighted scoring, and outputs to impact assessment for each of the 5 CAMBER components. This structured approach has been developed to facilitate project leadership, pilot site leads, and downstream work package leads.

In bringing together these key elements, this deliverable contributes to a total of 11 project key performance indicators (KPIs), as shown in Table 6. Moreover, completion of deliverable D2.2 marks the achievement of project milestone MS2: theoretical principles, methodological process and technical specifications for the development and testing of the CAMBER components. Implications for subsequent CAMBER work packages are presented next.

Table 6 — D2.2 contributions to project KPIs.

Project objective	Project KPI	Contribution in D2.2
Establish digital connections between road infrastructure elements and road, traffic and asset management and monitoring systems.	Updated catalogue of definitions for infrastructure data.	Definitions can be found in the 'Data Dictionary' in Annex 3.
	New-generation data source types validated	Foundations for validation of data sources have been described in Solution #2 (Annex 1). Performing the validation is to take place in WP5.
Develop safety performance criteria for urban and secondary	Safety assessment and analysis for each road user group (i.e. vehicle occupants,	Vehicle occupants as well as vulnerable road users are the focal point in solutions listed in Annex 1 and 2. In

Project objective	Project KPI	Contribution in D2.2
roads, accounting for all road users, to identify cost-effective upgrade solutions.	PTW, bicyclists, pedestrians, ADAS equipped vehicles).	pilot demonstrations, the FSI calculations will be aggregated by road user type, and ADAS equipped vehicles are targeted specifically in the CBA (Section 4).
	Asset and safety performance criteria with supporting metrics	Performance mechanisms have been described in the 'Data dictionary' (Annex 3); thresholds (e.g. on what constitutes 'safe performance') will need to be established in collaboration with pilot sites.
	Enhanced maintenance planning tool	Foundations for enhanced maintenance planning have been laid in several solutions in Annex 1.
Develop low-cost infrastructure measures to elicit safe road user behaviour and reduce the severity of crash outcomes on the secondary road network.	Innovative infrastructure safety measures tested in laboratory environment	Thirty interventions eligible for testing in laboratory and real world environments are listed in Annex 2, and considerations for testing have been described in the evaluation framework in Section 5.
	Measures tested in real world environment	
Discover and refine maintenance procedures and techniques for road infrastructure which can minimise traffic crashes and other impacts during the life cycle of secondary roads.	No. of maintenance techniques tested	Foundations for maintenance techniques have been laid in several solutions in Annex 1.
Demonstrate and prove concepts for optimised road safety and asset management on urban and secondary road networks.	Evaluation framework	The CAMBER evaluation framework is presented in Section 5.
	No. of cost-benefit analyses	Impact assessment methods have been described in Section 4, thereby laying the foundation for performing impact assessment in WP5.
	European-wide impact evaluation	

6.1 DATA COLLECTION, FUSION AND PROVISION (WP3)

The essential contribution of WP2 and specifically D2.2 to WP3 is a better understanding of what data to collect, in order to enable and support the project impact assessment and cost-benefit analysis. These topics are essential for all components evaluated in CAMBER, which in turn have their own data needs. WP3 needs to know the required data - to plan for collection activities at the pilot sites, as operationalized in tasks T3.3 (Ground Truth Data collection) and T3.4 (Dynamic Data collection). This is not limited to basic sensor data, but also contains information on what derived data (like measures of comfort or surrogate safety measures) is to be procured. This effort is supported for instance by D2.2 - 5.1.2 Pilot site testing, which gives a good overview of planned interventions and the CAMBER components they relate to, allowing to associate data needs.

This includes the question of whether particular assessments do in fact require physical data collection or will be evaluated entirely in virtual environments, as is outlined in D2.2 subchapter 5.3 for the different impact assessment options for the CAMBER components. Similarly, the modalities for carrying out CBA in CAMBER were well outlined in D2.2 - 4.3.1.2 and differentiated per CAMBER component.

For safety evaluation of interventions (cost-benefit analysis), the minimal data required was found to be localized crash data (total costs of crashes) (or SSM-proxies, which would have to be simulated or collected dynamically) in the pilot areas and the location of interventions for before-after evaluations. These base elements, which have to be obtained from the pilot sites, are typically augmented by information about the infrastructure elements & conditions nearby and ideally also by road user flows. This data will also be required for the more advanced FSI estimation (D2.2 - 4.3.2) to be carried out at the pilot sites as a reference standard. For this, video data from the pilot sites or physical in-person assessment will be required as well.

For road asset condition evaluation, road condition parameters will be needed to set up models of the deterioration and improvement of the road assets. These measures are foreseen to be collected in T3.3 and T3.4.

What is most helpful to WP3, is the mentioned expected benefits in D2.2 - 4.3.1.2 “Performing CBA”, as this indirectly declares the data needs for impact assessment.

For component 1, it can be gathered that data like emergency repairs, detection of hazards and resource allocation should be available to assess component 1. While the detection of hazards might be obtained from sources like BMOB’s Flitsmeister-App, typically these are sources that would need to be provided from the local road authority and thus need to be in the focus of WPs 3 and 5.

For component 2 “faster detection of defects, reduced survey costs, and enhanced decision accuracy” should ideally follow from the investigations made between the data coming from T3.3 & T3.4 and the development work in T3.5, with data collection & pilot engagement only needing to validate the findings.

For component 3 the focus on “reduced delay costs, lower asset degradation, and improved safety indicators” shows that again road maintenance data provided by the test site authorities will be needed. This might be challenging and requires close collaboration of WPs 3 & 5, as such data does not tend to be easily available.

For component 4 the mentioned impacts are “safety gains are estimated via simulation or SSM, considering crash-reduction potential under improved infrastructure conditions” and costs are

“infrastructure adaptation, data acquisition, and maintenance of digital connectivity.”. The data for safety gains is well within the intended data collection of T3.4 (although some video data might be needed), but the costs of infrastructure adaptation and digital infrastructure operation need to be obtained from the pilot sites.

For component 5 the needed data is most closely resembling the above-mentioned baseline situation of crash/SSM-data and road asset quality in an area affected by an intervention for before-after analyses. WP3 will engage with the pilot sites assess the availability of crash data and the options for collecting SSMs.

Key implications for WP3:

- The Data Dictionary should be shared with all pilots to avoid inconsistencies in variable naming, formatting, or semantic interpretation.
- Pilot sites should define and confirm the technical specifications and installation parameters of all sensing technologies (e.g., camera placement, resolution, frame rate) early in the process. This will allow to prepare and validate the data-processing pipelines in advance, ensuring that the collected data meets the quality requirements of the CAMBER Components.
- Data quality checks should be coordinated across WP3 and WP5 to ensure that all required fields for CBA and FSI estimation meet minimum thresholds for completeness.

6.2 SOLUTIONS INVESTIGATION AND DIGITAL TWINS (WP4)

Within WP2, tasks T2.3, T2.4, and T2.5 give WP4 the scope, priorities, and rules it must follow when investigating solutions and developing digital twins. WP4 designs and tests CAMBER solutions prior to the implementation on the pilots; however, the choice of solutions, the design of experiments and simulations, and the required indicators all originate from the work in WP2. In simple terms, WP2 defines what WP4 will test, and which data and outputs must be produced so that later impact assessment and comparison across pilots are possible.

Task T2.3 helps WP4 determine which solutions and interventions justify detailed technical effort. The solution inventory and its mapping to the five CAMBER components, integration types, expected changes, and use cases show where digital twins are most useful within road safety, traffic, and asset management. The long-list and shortlist of low-cost safety interventions, together with the 'which, where, and what' classification and the initial feasibility and compatibility screening, ensure that the interventions taken into WP4 are evidence-based, scalable, and realistic for the pilot authorities. These selections serve as the starting point for the simulations and digital twin concept configurations that will be developed in WP4.

Task T2.4 defines how WP4 will quantify the effects of both physical interventions and digital twin-oriented solutions. The impact typology and decision logic separate monetizable impacts, fatal and serious injury-related impacts, and broader qualitative effects, clarifying when to use cost-benefit analysis, FSI estimation, or alternative methods. WP4 must, therefore, design simulations, laboratory tests, and digital twin scenarios that align with these impact categories and can be used directly in early- and late-stage CBA as well as in FSI-reduction estimates for pilots and extrapolated networks.

Task T2.5 translates the concepts from Tasks T2.3 and T2.4 into one unified testing and evaluation framework that WP4 must apply. It defines shared data requirements, establishes a data dictionary, and introduces procedures for collecting quantitative and qualitative indicators in simulation, laboratory, and pilot environments. It also integrates safety, cost, scalability, and transferability into comparable results across solutions and components. For WP4, this means that all solution investigations and digital twin developments must follow the agreed-upon indicator set, data structures, and evaluation logic, ensuring their outputs can seamlessly integrate into the impact assessment in Task T2.4 and the cross-component evaluation in WP5.

Key implications for WP4:

- Confirm early which interventions will be modelled for each pilot, based on the shortlisted set identified in this deliverable, to allow time for efficient scenario generation.
- Ensure that surrogate-safety modelling assumptions (e.g., TTC thresholds) are aligned across partners before simulation begins.
- Where digital-twin inputs depend on local calibration factors (e.g., traffic mix), pilot sites should provide supporting evidence as early as possible.

6.3 PILOT TESTING AND EVALUATION (WP5)

D2.2 has direct implications for how the CAMBER pilots will design, implement, and evaluate the selected solutions. The CAMBER pilots must operationalise a coherent set of CAMBER solutions across the five components. The mapping of solutions to the strategic–tactical–operational hierarchy requires each pilot to understand where its selected solutions sit within this structure and ensure the corresponding decision processes, data flows and organisational roles are in place. Because many solutions involve cross-component dependencies—such as data sources feeding digital twin models or safety attributes informing maintenance planning—pilots must plan for coordinated implementation rather than isolated testing of individual elements. This includes establishing data acquisition arrangements early, engaging asset and safety teams jointly, and aligning pilot objectives with the expected performance changes described in Chapter 2.

Pilots must articulate, in advance, what each intervention is expected to achieve, how this aligns with strategic or operational safety objectives, and which hypotheses or evidence gaps their deployment will help test. This supports both internal planning and the eventual contributions to CAMBER’s Key Exploitable Result 7.

The solution identification framework described in Chapter 2 signals to pilots that they will need to verify the feasibility, relevance, and maturity of each selected solution within their local contexts. Several solutions address integration at the tactical or operational input levels, which may require access to maintenance logs, incident data, traffic and user information, and operational procedures. Pilots will therefore need to assess institutional readiness, data availability and system compatibility to ensure that solutions can be meaningfully demonstrated. Where solutions involve digital technologies or cross-departmental processes, pilots should anticipate the need for close coordination with WP3 and WP4 to ensure that testing environments and operational practices support the intended outcomes.

For piloting the low-cost interventions identified for Component 5, the screening and evaluation processes developed in Chapter 3 provide a structured foundation that the pilots must operationalise,

ensuring that each selected intervention meets the feasibility, compatibility, and acceptability requirements prior to deployment. Based on this, pilots will need to revisit the co-created intervention to:

- Confirm that interventions are physically and operationally deliverable and that they align with existing maintenance capabilities and regulatory frameworks, and
- Adapt (where necessary) design elements and implementation priorities to ensure that selected measures are not only evidence-informed, but also context-appropriate and supported by local stakeholders.
- Conduct structured assessments of user exposure, vulnerability, and potential adverse effects, ensuring that interventions do not inadvertently transfer risk to other groups or locations.

For those interventions which have incomplete or weak evidence bases (particularly in relation to cost-effectiveness, impacts on different road users, and benefit–cost ratios), the demonstration will also serve to generate much-needed empirical evidence to fill these gaps. Pilots must therefore plan their implementation in a way that supports robust data collection and evaluation, targeting those aspects of interventions that are least understood in the literature.

The deliverable also connects the screening outcomes with the broader evaluation and impact assessment requirements detailed in Chapters 4 and 5. Each pilot must structure data collection, monitoring periods, and evaluation methods to align with the harmonised indicators and testing procedures set out in the evaluation framework. This means that before–after studies, ground-truth validation, surrogate safety analysis, and maintenance or operational data collection need to be integrated directly into the implementation planning for each selected intervention. Several interventions identified as compatible with digital twin asset inventories or dependent on complementary technologies will require close coordination with WP3 and WP4. Pilots must ensure that data ecosystems, DT configurations, and operational processes are ready to support the interventions’ intended functions and evaluation requirements.

Finally, the deliverable places responsibility on the pilots to generate transferable insights that can support Europe-wide scaling and guidance. The pilots must therefore document contextual factors—physical, institutional, behavioural and socio-political—that influence intervention performance and determine transferability. By doing so, the pilot results will feed directly into future best-practice guidance, ensuring that CAMBER’s low-cost infrastructure measures can be effectively adapted to diverse European settings.

Key implications for WP5:

- Pilot teams must secure all necessary permissions for data collection technologies, including video sensors and roadside equipment, well before deployment.
- Pilot teams should plan sufficient time for iterative testing, including the possibility of re-running tests if indicators or data completeness requirements are not initially met.
- Evaluation outputs (e.g., indicator values, SSM results, processed datasets) should follow a standard reporting template to ensure compatibility with WP4 and WP5 impact-assessment workflows.

7 References

- Aleksa, M., Schaub, A., Erdelean, I., Wittmann, S., Soteropoulos, A., & Fördös, A. (2024). Impact analysis of Advanced Driver Assistance Systems (ADAS) regarding road safety–computing reduction potentials. *European Transport Research Review*, 16(1), 39.
- Alexander, G. J., & Lunenfeld, H. (1972). "Satisfying Motorists Needs for Information", *Traffic Engineering*, Vol. 42, No. 1, p. 46-70.
- Aloupogianni, E., Doctor, F., Karyotis, C., Maniak, T., Tang, R., & Iqbal, R. (2024). An AI-Based Digital Twin Framework for Intelligent Traffic Management in Singapore. 2024 International Conference on Electrical, Computer and Energy Technologies (ICECET), 1–6. <https://doi.org/10.1109/ICECET61485.2024.10698642>
- Anthony, R. N. (1965). *Planning and Control Systems: A Framework for Analysis*. City: Harvard Business School Press.
- Armstrong, P. (2002). The costs of activity-based management. *Accounting, Organizations and Society*, 27(1), 99–120. [https://doi.org/10.1016/S0361-3682\(99\)00031-8](https://doi.org/10.1016/S0361-3682(99)00031-8)
- Asselin-Miller, N., Biedka, M., Gibson, G., Kirsch, F., Hill, N., White, B., & Uddin, K. (2016). Study on the Deployment of C-ITS in Europe (Framework Contract on Impact Assessment and Evaluation Studies in the Field of Transport No. MOVE/C.3/No. 2014-795). European Commission. <https://transport.ec.europa.eu/system/files/2016-10/2016-c-its-deployment-study-final-report.pdf>
- Australian Government Department of Infrastructure, Regional Development, Communications and the Arts (DITRDCA) (2023). National Road Safety Action Plan 2023–25. <https://www.infrastructure.gov.au/sites/default/files/documents/national-road-safety-action-plan-2023-25.pdf>
- Austroroads. (2023). AusRAP Strategy & Business Plan 2023–2025. <https://irap.org/2023/09/ausrap-news-80-of-travel-on-3-star-or-better-roads-by-2030/>
- Ayomoh, M., & Ongwae, B. (2025). A Systematic Review of Asset Integrity and Process Safety Management Sustainability for Onshore Petrochemical Installations. *Sustainability*, 17(1), 286. <https://doi.org/10.3390/su17010286>
- Basile, O., Persia, L., & Usami, D. S. (2010). A methodology to assess pedestrian crossing safety. *European Transport Research Review*, 2(3), 129–137. <https://doi.org/10.1007/s12544-010-0036-z>
- Bickel, P. et al. (2006). Proposal for harmonised guidelines. EU project HEATCO Deliverable 5. University of Stuttgart, Stuttgart.
- Bjorvatn, A., Page, Y., Fahrenkrog, F., Weber, H., Aittoniemi, E., Heum, P., Lehtonen, E., Silla, A., Bärgrman, J., Borrack, M., Innamaa, S., Itkonen, T., Malin, F., Perderson, K., Schuldes ika, M., Sintonen, H., Streubel, T., Hagleitner, W., Hermitte, T., ... Torrao, G. (2021). L3 Pilot Driving Automation (Impact Evaluation Results No. Deliverable D7.4). European Union. https://l3pilot.eu/fileadmin/user_upload/Downloads/Deliverables/Update_14102021/L3Pilot-SP7-D7.4-Impact_Evaluation_Results-v1.0-for_website.pdf

Blincoe, L., Miller, T., Wang, J.-S., Swedler, D., Coughlin, T., Lawrence, B., Guo, F., Klauer, S., & Dingus, T. (2023). The economic and societal impact of motor vehicle crashes, 2019 (Revised). National Highway Traffic Safety Administration, Washington DC.

Bliss, T., & Breen, J. (2009). Road Safety Management Capacity Reviews and Safe System Projects Guidelines.

<https://documents1.worldbank.org/curated/en/400301468337261166/pdf/842030WPOENGLIOBox0382132B00PUBLIC0.pdf>

Borghetti, F., Beretta, G., Bongiorno, N., & De Padova, M. (2024). Road infrastructure maintenance: Operative method for interventions' ranking. *Transportation Research Interdisciplinary Perspectives*, 25, 101100. <https://doi.org/10.1016/j.trip.2024.101100>

Bützer, D., Wijnen, W., Elvik, R., Pokorny, P. (2022), Cost-benefit analysis of innovative automotive safety systems, Deliverable 6.1 of the H2020 project VIRTUAL.

Byaruhanga, C. B., & Evdorides, H. (2024). The impact of indirect benefits (reduced travel time, fuel use and emissions) in cost benefit analysis of road safety countermeasures. *Traffic Injury Prevention*, 25(3), 434–439. <https://doi.org/10.1080/15389588.2024.2322665>

Cardoso, J. L. (2005). Safety Assessment for Design and Redesign of Horizontal Curves. 3rd International Symposium on Highway Geometric Design, Chicago, Illinois. <https://trid.trb.org/View/760722>

Cardoso, J. L., Lisboa Santos, J., & Lima Azevedo, C. (2010). Comparative Safety Analysis of a Two-Lane Two-Way Major Highway, Using IHSDM and a Portuguese Procedure. MIT. https://web.mit.edu/cami/Public/CLA_IHSDM_TRB_2011.pdf

Cardoso, J. L., Roque, C., Vieira, S., ..., & Sadeqi Bajestani, M. (2025). State of the art and gap analysis. Deliverable D2.1 of the Horizon Europe project CAMBER. <https://CAMBER-project.eu/>

Coito, T., Martins, M. S. E., Firme, B., Figueiredo, J., Vieira, S. M., & Sousa, J. M. C. (2022). Assessing the impact of automation in pharmaceutical quality control labs using a digital twin. *Journal of Manufacturing Systems*, 62, 270–285. <https://doi.org/10.1016/j.jmsy.2021.11.014>

Committee on Motor Vehicle Traffic Accident Classification (1996). American National Standard — Manual on Classification of Motor Vehicle Traffic Accidents (Sixth Edition). Itasca IL: National Safety Council.

Dahdah S., McMahon K. (2008). The true cost of road crashes. Valuing life and the cost of a serious injury. iRAP <https://resources.irap.org/Research/iRAP%20report%20-%20the%20true%20cost%20of%20road%20crashes%20-%20ESP.pdf>

Daniels, S., Martensen, H., Schoeters, A., Van den Berghe, W., Papadimitriou, E., Ziakopoulos, A., Kaiser, S., Aigner-Breuss, E., Soteropoulos, A., Wijnen, W., Weijermars, W., Carnis, L., Elvik, R., & Perez, O. M. (2019). A systematic cost-benefit analysis of 29 road safety measures. *Accident Analysis & Prevention*, 133, 105292. <https://doi.org/10.1016/j.aap.2019.105292>

de Leur, P., & Hill, D. (2015). Quantification of Road Safety Risk at Locations Without Collisions to Justify Road Safety Investments. *Transportation Research Record: Journal of the Transportation Research Board*, 2513, Article 15–2981. <https://trid.trb.org/View/1337859>

Department for Transport, & Arup. (2024). Integrated network management digital twin: Economic benefits analysis [Digital Twins economic benefits analysis]. Department for Transport. <https://www.gov.uk/government/publications/integrated-network-management-digital-twin-economic-benefits-analysis>

DGT (2020). Recomendaciones para la mejora de la Seguridad Vial en entornos interurbanos, Madrid, Spain (https://www.dgt.es/export/sites/web-DGT/.galleries/imagenes/muevete-con-seguridad/tecnologia-e-innovacion-en-carretera/recomendaciones-en-entornos-interurbanos/ALTA_-_Libro-DGT-Medidas-Interurbanas.pdf).

Diop, I., Abdul-Nour, G., & Komljenovic, D. (2024). Integrated Decision-Making Framework in Industrial Asset Management for Assessing and Managing Emerging Risks. In G. Abdul-Nour, M. Ngoc Dinh, T. Seecharan, A. Crespo Márquez, D. Komljenovic, J. Amadi-Echendu, & J. Mathew (Eds), 17th WCEAM Proceedings (pp. 241–254). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-59042-9_20

Dirección General de Tráfico (2022). Recomendaciones para la mejora de la Seguridad Vial en entornos interurbanos. Ministerio del Interior, Madrid.

Elbert, R., Schaffhauser-Linzatti, M., Kotzab, H., & Friedrich, H. (2020). Tactical network planning and design in multimodal transportation – A systematic literature review. In Lecture Notes in Logistics. Springer.

Elvik, R., Høyve, A., Vaa, T., & Sørensen, M. (2009). The handbook of road safety measures. Emerald Group Publishing Limited.

ERSO. (2018). Cost Benefit Analysis [CBA guide]. European Road Safety Observatory. <https://road-safety.transport.ec.europa.eu/system/files/2021-07/ersosynthesis2018-costbenefitanalysis.pdf> European Commission. (2014). Guide to Cost-Benefit Analysis of Investment Projects [Economic appraisal tool for Cohesion Policy 2014-2020]. European Commission. https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf

European Commission. (2020). Next steps towards 'Vision Zero' [EU Road Safety Policy Framework 2021-2030]. European Commission. <https://op.europa.eu/o/opportal-service/download-handler?identifer=d7ee4b58-4bc5-11ea-8aa5-01aa75ed71a1&format=pdf&language=en&productionSystem=cellar>

FAME. (2025). European Common Evaluation Methodology Handbook for Connected, Cooperative and Automated Mobility (EU-CEM Handbook for CCAM) [Hanbook for CCAM]. European Union. <https://www.connectedautomateddriving.eu/methodology/eu-cem-handbook-for-ccam/>

Fancello, G., Carta, M., & Serra, P. (2020). Data Envelopment Analysis for the assessment of road safety in urban road networks: A comparative study using CCR and BCC models. Case Studies on Transport Policy, 8(3), 736–744. <https://doi.org/10.1016/j.cstp.2020.07.007>

Federal Highway Administration (2025). Crash Modification Factors Clearinghouse. Accessed November 28, 2025. <https://cmfclearinghouse.fhwa.dot.gov/>.

Federal Highway Administration (FHWA), & American Association of State Highway and Transportation Officials (AASHTO). (2013). Transportation Asset Management Guide: A Focus on Implementation. <https://www.fhwa.dot.gov/asset/pubs/hif13047.pdf>

Feig, P., Schatz, J., Gschwendtner, K., Borrack, M., & Lienkamp, M. (2017). Monetary and prospective benefit assessment method for advanced driver assistance systems. In *Proc. 25th Int. Tech. Conf. Enhanced Safety of Vehicles*.

FOT-NET. (2011). Field Operational Tests Support Action [ICT for Intelligent Vehicles and Mobility Services]. European Union. <https://cordis.europa.eu/project/id/214853>

Garach, L., Calvo, F., & De Oña, J. (2022). The effect of widening longitudinal road markings on driving speed perception. *Transportation Research Part F: Traffic Psychology and Behaviour*, 88, pp. 141-154. <https://doi.org/10.1016/j.trf.2022.05.021>

Griffin, L.I., & Reinhardt, R.N. (1996). A Review of Two Innovative Pavement Patterns that Have Been Developed to Reduce Traffic Speeds and Crashes. DOT Report. Washington, D.C., AAA Foundation for Traffic Safety.

Godthelp, H., Wesemann, P., Stipdonk, H., & King, M. (2024). Capacity building for road safety in LMICs: the need for a sustainable local knowledge and research infrastructure. *Traffic Safety Research*, 8, (pp. e000063).

Goodhue, D. L., Wybo, M. D., & Kirsch, L. J. (1992). The Impact of Data Integration on the Costs and Benefits of Information Systems. *MIS Quarterly*, 16(3), 293–311. <https://doi.org/10.2307/249530>

Havránek, P., Zůvala, R., Špaňhel, J., Herout, A., Valentová, V., & Ambros, J. (2020). How does road marking in horizontal curves influence driving behaviour? *European Transport Research Review*, 12(33). <https://doi.org/10.1186/s12544-020-00425-7>

Hula, A., Fürsinn, F., Schwieger, K., Saleh, P., Neumann, M., & Ecker, H. (2021). Deriving a joint risk estimate from dynamic data collected at motorcycle rides. *Accident Analysis & Prevention*, 159, 106297. <https://doi.org/10.1016/j.aap.2021.106297>

Hussain, Q., Alhajyaseen, W.K.M., Kharbecke, M., & Almallah, M. (2023). Safer pedestrian crossing facilities on low-speed roads: comparison of innovative treatments. *Accident Analysis & Prevention*, 180, 106908. <https://doi.org/10.1016/j.aap.2022.106908>

Innamaa, S., Smith, S., Barnard, Y., Rainville, L., Rakoff, H., Horiguchi, R., & Gellerman, H. (2018). Trilateral Impact Assessment Framework for Automation in Road Transportation. Trilateral Impact Assessment Sub-Group for ART. https://www.connectedautomateddriving.eu/wp-content/uploads/2018/03/Trilateral_IA_Framework_April2018.pdf

iRAP. (2022). The Road Safety Toolkit [Road Safety Toolkit]. iRAP. <https://toolkit.irap.org/>

iRAP. (n.d.-a). Crash Risk Mapping. Retrieved 11 November 2025, from <https://irap.org/rap-tools/crash-data/crash-risk-mapping/>

iRAP. (n.d.-b). iRAP Methodology fact sheets [iRAP methodology factsheets]. Retrieved 11 November 2025, from <https://irap.org/methodology/>

iRAP. (n.d.-c). Safer Roads Investment Plans [Safer Roads Investments Plans (SRIP)]. iRAP. Retrieved 6 November 2025, from <https://irap.org/rap-tools/investment-planning/safer-roads-investment-plans/>

Jayarathne, M., Nallaperuma, D., De Silva, D., Alahakoon, D., Devitt, B., Webster, K. E., & Chilamkurti, N. (2019). A data integration platform for patient-centered e-healthcare and clinical decision support. *Future Generation Computer Systems*, 92, 996–1008. <https://doi.org/10.1016/j.future.2018.07.061>

Jiao, B., & Evdorides, H. (2024). Methods of strategic road safety management: a systematic review. *International Journal of Injury Control and Safety Promotion*, 31 (3), (pp. 420–430).

Kamal, H., Yáñez, W., Hassan, S., & Sobhy, D. (2024). Digital-Twin-Based Deep Reinforcement Learning Approach for Adaptive Traffic Signal Control. *IEEE Internet of Things Journal*, 11(12), 21946–21953. <https://doi.org/10.1109/JIOT.2024.3377600>

Karunaratne, T., Ajjero, I. R., Joseph, R., Farr, E., & Piroozfar, P. (2025). Evaluating the Economic Impact of Digital Twinning in the AEC Industry: A Systematic Review. *Buildings*, 15(14), 2583. <https://doi.org/10.3390/buildings15142583>

Martensen, H., Daniels, S., Van Den Berghe, W., Wijnen, W., Weijermars, W., Carnis, L., Saadé, J., & Elvik, R. (2018). Guidelines for Priority Setting Between Measures with Practical Examples [Deliverable Number 3.5 of the H2020 project SafetyCube.]. SafetyCube. <https://www.SafetyCube-project.eu/wp-content/uploads/SafetyCube-D3.5-GuidelinesForPrioritySettingBetweenMeasuresWithPracticalExamples.pdf>

Masello, L., Castignani, G., Sheehan, B., Murphy, F., & McDonnell, K. (2022). On the road safety benefits of advanced driver assistance systems in different driving contexts. *Transportation research interdisciplinary perspectives*, 15, 100670.

Masello, L., Castignani, G., Sheehan, B., Murphy, F., & McDonnell, K. (2022). On the road safety benefits of advanced driver assistance systems in different driving contexts. *Transportation Research Interdisciplinary Perspectives*, 15, 100670. <https://doi.org/10.1016/j.trip.2022.100670>

Metz, B., Rösener, C., Louw, T., Aittoniemi, E., Bjorvatn, A., Wörle, J., Weber, H., Antas Torrao, G., Silla, A., Innamaa, S., Fahrenkrog, F., Heum, P., Pedersen, K., Merat, N., Nordhoff, S., Beuster, A., Dotzauer, M., & Streubel, T. (2019). L3 Pilot Driving Automation (Evaluation Methods No. Deliverable D3.3). European Union. https://l3pilot.eu/fileadmin/user_upload/Downloads/Deliverables/Update_07102021/L3Pilot-SP3-D3.3_Evaluation_Methods-v1.0_for_website.pdf

Michon, J. A. (1985). A critical view of driver behavior models: What do we know, what should we do? In L. Evans & R. C. Schwing (Eds.), *Human Behavior and Traffic Safety* (pp. 485–520). Plenum Press.

Miller, G. A., Galanter, E., & Pribram, K. H. (1960). *Plans and the Structure of Behavior*. City: Holt, Rinehart and Winston.

Mitsakis, E., Kotsi, A., Lu, M., SHCHURYK, O., Malone, K., & Pillado, M. (2018). C-Mobile (D2.1 Ex-Ante Cost-Benefit Analysis) [Accelerating C-ITS Mobility Innovation and deployment in Europe]. European Union. <https://c-mobile-project.eu/wp-content/uploads/sites/19/2018/03/C-MOBILE-D2.1-Ex-ante-cost-benefit-analysis-v1.1-FINAL-1.pdf>

National Technical University of Athens, University of Zagreb, & FRED Engineering s.r.l. (2023). Network Wide Road Safety Assessment [Methodology and Implementation Handbook for a Network-wide Road Safety Assessment]. European Commission. https://road-safety.transport.ec.europa.eu/eu-road-safety-policy/priorities/infrastructure/road-infrastructure-guidelines_en

Neass, K. (2015). Traffic Forecasting at 'Strategic', 'Tactical' and 'Operational' Level. Transport Research Arena (TRA) 2014 Proceedings, Paris.

Nilsson, N. J. (1984). Shakey the Robot.

NZTA. (2024). Infrastructure Risk Rating Manual. NZ Transport Agency Waka Kotahi. <https://www.nzta.govt.nz/assets/resources/infrastructure-risk-rating-manual/infrastructure-risk-rating-manual-update-30-october-2024.pdf>

Phillips-Wren, G., Mora, M., Forgionne, G. A., & Gupta, J. N. D. (2009). An integrative evaluation framework for intelligent decision support systems. *European Journal of Operational Research*, 195(3), 642–652. <https://doi.org/10.1016/j.ejor.2007.11.001>

PIARC. (2024). Prioritisation & Assessments | Road Safety Manual—PIARC (World Road Association) [Road Safety Manual]. <https://roadsafety.piarc.org/en/planning-design-operation/intervention-selection/prioritisation-assessments>

PIARC. (2025). Road Safety Manual—PIARC (World Road Association) | Road Safety Manual A guide for practitioners ! <https://roadsafety.piarc.org/en>

Pirdavani, A., Bajestani, M. S., Bunjong, S., & Delbare, L. (2025). The Impact of Perceptual Road Markings on Driving Behavior in Horizontal Curves: A Driving Simulator Study. *Applied Sciences*, 15(8), 4584. <https://doi.org/10.3390/app15084584>

Pizzicori, M., Piantini, S., Lucci, C., Cordellieri, P., Pierini, M., & Savino, G. (2025). Retrofitting ADAS for Enhanced Truck Safety: Analysis Through Systematic Review, Cost–Benefit Assessment, and Pilot Field Testing. *Sustainability*, 17(11), 4928.

Psarommatis, F. & May, G. A standardized approach for measuring the performance and flexibility of digital twins. *Int. J. Prod. Res.* 61, 6923–6938 (2023)

Putatunda, A., Haddad, C. A., & Antoniou, C. (2025). A comprehensive review of the socio-economic appraisal methodologies of the road safety measures. *Accident Analysis & Prevention*, 217, 108021. <https://doi.org/10.1016/j.aap.2025.108021>

Roque, C., & Cardoso, J. L. (2015). SAFESIDE: A computer-aided procedure for integrating benefits and costs in roadside safety intervention decision making. *Safety Science*, 74, 195–205. <https://doi.org/10.1016/j.ssci.2015.01.001>

Sartori, D., Catalano, G., Genco, M., Pancotti, C., Sitori, E., Vignetti, S., & Del Bo, C. (2014). Guide to Cost-Benefit Analysis of Investment Projects [Economic appraisal tool for Cohesion Policy 2014-2020]. European Commission. https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf

Sartori, D., Marra, M., Swerdlow, R., Angelini, F., Bruzge, S., Danev, N., Fagiani, P., Riley, P., Trace, F., Raducu, A., Kristl, M., Knast-Braczkowska, J., Schaller, M., Marcincak, M., Mertens, C., Valentine, K., Koziarkiewicz, A., Lupascu, A. M., Calvete, T., & Carpenter, G. (2021). Economic Appraisal Vademecum 2021-2027 [General Principles and Sector Applications]. European Commission. <https://jaspers.eib.org/files/library/2021/economic-appraisal-vademecum-2021-2027-general-principles-and-sector-applications.pdf>

Schoeters, A., Large, M., Koning, M., Carnis, L., Daniels, S., Mignot, D., ... & van der Horst, M. (2022). Economic valuation of preventing fatal and serious road injuries. Results of a Willingness-To-Pay study in four European countries. *Accident Analysis & Prevention*, 173, 106705.

Siegel, M. (2003). The Sense–Think–Act Paradigm Revisited. Proceedings of the 1st International Workshop on Robotic Sensing (ROSE'03), Örebro, Sweden.

StadieSeifi, M., Dellaert, N. P., Nuijten, W., Van Woensel, T., & Raoufi, R. (2014). Multimodal freight transportation planning: A literature review. *European Journal of Operational Research*, 233 (1), (pp. 1–15).

Studer, L., Frötscher, A., Crockford, G., Gandini, P., Marchionni, G., Netten, B., Vlassenroot, S., Kwakernaat, H., Zimmermann, W., Wadsworth, P., Gutiérrez Lanza, S., Innamaa, S., Schirokoff, A., & Allen, T. (2023). C-Roads (Evaluation and Assessment Plan No. Version 1.3). European Union. https://www.c-roads.eu/fileadmin/user_upload/media/Dokumente/C-Roads_WG3_Evaluation_and_Assessment_Plan_version_1.3_Final.pdf

Svechin, A. A. (1923). *Strategy*. City: Voениzdat.

Tang, Z., Zhuang, D. & Zhang, J. Evaluation framework for domain-specific digital twin platforms. *Sci Rep* 15, 10544 (2025). <https://doi.org/10.1038/s41598-024-82154-8>

Tang, Z., Zhuang, D., & Zhang, J. (2025). Evaluation framework for domain-specific digital twin platforms. *Scientific Reports*, 15(1), 10544. <https://doi.org/10.1038/s41598-024-82154-8>

Teece, D. J. (2007). Explicating Dynamic Capabilities: The Nature and Microfoundations of (Sustainable) Enterprise Performance. *Strategic Management Journal*, 28 (13), (pp. 1319–1350).

Thiessen, P., Collins, J., Buckland, T., & Abbell, R. (2017). Valuing the wider benefits of road maintenance funding. *Transportation Research Procedia*, 26, 156–165. <https://doi.org/10.1016/j.trpro.2017.07.016>

Thomas, D. (2024). Economics of Digital Twins (NIST Advanced Manufacturing Series (NIST AMS 100-61)) [Costs, Benefits, and Economic Decision Making]. National Institute for Standards and Technology. <https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.100-61.pdf>

Toraldo, E., Novati, N., Rossi, D., & Ketabdari, M. (2025). A Novel Methodology for Planning Urban Road Safety Interventions. *Applied Sciences*, 15(4), 1993. <https://doi.org/10.3390/app15041993>

Uhlenkamp, J.-F., Hauge, J. B., Broda, E., Lütjen, M., Freitag, M., & Thoben, K.-D. (2022). Digital Twins: A Maturity Model for Their Classification and Evaluation. *IEEE Access*, 10, 69605–69635. <https://doi.org/10.1109/ACCESS.2022.3186353>

UK Roads Liaison Group (UKRLG), & Highways Maintenance Efficiency Programme (HMEP). (2013). Highway Infrastructure Asset Management: Guidance Document. <https://ukrlg.ciht.org.uk/asset-management/>

United Nations Economic Commission for Europe (UNECE). (2021). Tools for Asset Management: TEM Recommendations for Road Operators. <https://unece.org/sites/default/files/2021-05/Tools%20Asset%20TEM.pdf>

V4SAFETY Project (2025a), V4SAFETY Safety Cost Benefit Tool, <https://v4safetyproject.eu/outputs/v4safety-cost-benefit-analysis-tool-0.5.xlsx>, retrieved 3.November.2025

V4SAFETY Project (2025b), V4SAFETY CBA Tool Guidelines, <https://v4safetyproject.eu/outputs/user-guidelines-for-v4safety-cost-benefit-analysis-tool.pdf>, retrieved 3.November.2025

Vaughan, J. L., Leming, M. L., Liu, M., & Jaselskis, E. (2013). Cost-Benefit Analysis of Construction Information Management System Implementation: Case Study. *Journal of Construction Engineering and Management*, 139(4), 445–455. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000611](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000611)

Waters, G. (2025). Testing, Evaluation, Verification and Validation (TEVV) of Digital Twins: A Comprehensive Framework. *ArXiv*, abs/2507.04555.

Wijlhuizen, Dr. G. J., Dijkstra, D. A., & van Petegem, J. W. H. (2014). Safe Cycling Network (Developing a System for Assessing the Safety for Cycling Infrastructure No. R-2014-14E). SWOV Institute for Road Safety Research. <https://swov.nl/system/files/publication-downloads/r-2014-14e.pdf>

Wijnen, W. (2025). V4Safety [User guidelines for the V4SAFETY cost-benefit analysis tool]. European Union. <https://v4safetyproject.eu/media/pages/outputs/27469756ce-1762419222/user-guidelines-for-v4safety-cost-benefit-analysis-tool.pdf>

Wijnen, W., Dahdah, S., & Pkhikidze, N. (2025). The value of a statistical life in the context of road safety: a new value transfer approach. *Traffic Injury Prevention*, 1-8. <https://www.tandfonline.com/doi/epdf/10.1080/15389588.2025.2476607?needAccess=true>

Wijnen, W., Weijermars, W., Schoeters, A., van den Berghe, W., Bauer, R., Carnis, L., Elvik, R., & Martensen, H. (2019). An analysis of official road crash cost estimates in European countries. *Safety Science*, 113, 318–327. <https://doi.org/10.1016/j.ssci.2018.12.004>

Wijnen, W., Weijermars, W., Vanden Berghe, W., Schoeters, A., Bauer, R., Carnis, L., Elvik, R., Theofilatos, A., Filtness, A., Reed, S., Perez, C., and Martensen, H. 2017. Crash cost estimates for European countries. Deliverable 3.2 of the H2020 project SafetyCube.

World Road Association (PIARC). (2019). Asset Management Manual. <https://road-asset.piarc.org/>

World Road Association (PIARC). (2022). Road Network Operations / Intelligent Transport Systems (RNO/ITS) Manual. <https://rno-its.piarc.org/>

World Road Association (PIARC). (2023). Interactive Electronic Manuals — PIARC. <https://www.piarc.org/en/activities/online-manuals>

Yan, Y., Ni, L., Sun, L., Wang, Y., & Zhou, J. (2025). Digital Twin Enabling Technologies for Advancing Road Engineering and Lifecycle Applications. *Engineering*, 44, 184–206. <https://doi.org/10.1016/j.eng.2024.12.017>

Ziakopoulos, A., & Yannis, G. (2020). A review of spatial approaches in road safety. *Accident Analysis & Prevention*, 135, 105323. <https://doi.org/10.1016/j.aap.2019.105323>

Zirra, D., Perju-Mitran, A., Căruțașu, G., Pîrjan, A., & Cristache, S. E. (2022). A Cost-Benefit Approach for Analysing the Impact of eCall Technology on the EU Passenger Vehicles. *Engineering Economics*, 33(2), 143–160. <https://doi.org/10.5755/j01.ee.33.2.29321>

ANNEXES

ANNEX 1: CAMBER SOLUTIONS

This annex provides details on the development of solutions #1-#16 described in Section 2.3, which have been documented through a standardized format shown below:

Solution item	Instruction
Description	Summary of the solution.
Addressed gap	Which research gap identified in CAMBER deliverable D2.1 is addressed by this solution? Gaps can be found in sections 3.4, 4.7, and 5.1-5.5. If no previously identified gap is being addressed, use the default: "New solution".
CAMBER components	Explain which of the following CAMBER project components are addressed by the solution. Choose between 'yes', 'no', or 'partially' (e.g. in case of an indirection contribution), and provide a short statement to explain why. <ol style="list-style-type: none"> 1. Safety-integrated maintenance systems and processes. 2. New generation data sources. 3. Digital twins. 4. CCAM / ADAS performance. 5. Low-cost safety interventions
Integration type	Explain at which hierarchical levels (i.e. strategic, tactical, operational_in, operational_out, or 'X' for none of the above) the solution facilitates integration between three systems: road safety, road traffic, and road asset management, respectively. E.g. {operational_in, X, tactical}.
Change	Define the envisioned 'change' resulting from implementation of the solution (e.g. a higher inspection rate, increased level of detail on a certain measure, process change, a new opportunity that becomes available).
Use cases	Optional: Identify whether the 'change' applies only to certain use cases , e.g. pothole identification, surface treatment.
Result	Identify the result of the change (per use case, if applicable). Formulate outcome measures that can be used in T2.4/T2.5, and indicate whether these outcome measures are qualitative or quantitative , and in case of the latter if they are monetizable .
Limitations	Identify limitations of the solution , including costs and potential legal or practical issues
Relationships	Identify relationships with other solutions. Does this solution enable or facilitate another solution? Can this solution be used together with other solutions? If so, mention this (e.g. 'Enables solution #4').
Additional information	Any further elaboration / explanation. This may include why a solution is (not) applicable to certain pilot sites

#1 – ROADSIDE CAMERAS

Description	<p>Applications of cameras in road asset management and road safety are plentiful, due to the flexibility of the available camera types. Static and mobile cameras offer differing potential, and their usage profits considerably from recent developments in object detection and tracking.</p> <p>Mobile cameras can be a means to track the safety of road user interactions (detecting incidents and metrics of safe interaction) and to acquire updates on road infrastructure condition (condition/placement of road inventory and/or pavements).</p> <p>Static cameras can be a means to accurately acquire moment-to-moment road user movements in a given area. This information can be used to react in almost rel-time to safety challenges (e.g. risky interactions, detections of crashes) and functioning of the infrastructure (e.g., blocked paths, traffic jams reaching into the camera domain of vision). In the form of webcams, they may allow for manual inspection/verification of a detected incident at any point and provide data flows to optimize systems of traffic regulation or assess effectiveness of interventions through detected changes in traffic flows/vehicle movements.</p>
Addressed Gap	<p>Addresses availability of objective safety and traffic data, potentially in real time.</p> <p>Allows for effectiveness analyses of safety measures.</p> <ul style="list-style-type: none"> • Thus this addresses: Data Interoperability and Methodological Transferability (All points if evaluation is standardized) • Data sparsity in rural areas and for vulnerable road users (through targeted local deployment of video collection) • Modal and temporal underrepresentation (in the area of camera use all modes within the field of vision can be observed) • Behavioural and Human-Factor Gaps (through observational data and tracking)
CAMBER components	<ol style="list-style-type: none"> 1. Partially, camera can acquire traffic flows and thus strain on the infrastructure. To acquire safety relevant information additional processing has to be active (identifying dangerous situations/crashes) 2. Yes, through video acquisition, indicators on both safety and asset management (local traffic flows) can be defined and calculated 3. Partially, in the sense that information from camera solutions can be integrated in digital twins, either as near real time data or through statistical mapping 4. Partially, if information (safety or traffic situation) from the cameras is processed and provided to connected vehicles. 5. Partially. A local camera solution is relatively low-cost. However, it also covers only a small area (appr. 80 – 100m) of the network. Scale ups can be costly, depending on the desired coverage.

Integration type	<p>This solution covers primarily the operational and the tactical level in all three categories, as cameras tend to be used in a spatially (and often also temporally) limited domain.</p> <p>{Operational_in/Tactical, Operational_in/Tactical, Operational_in/Tactical}</p>
Change	<p>Enables fast incident detection and thus near real-time responses (to crashes, traffic jams or infrastructure failures). Data collection with cameras can be used for systematic risk assessments and impact analyses (before – after analyses) both for changes in road user movements/flows or road user conflicts (through the use of surrogate safety measures).</p>
Use cases	<p>Relevant option to assess changes in road user movements in a particular limited area that can be covered with cameras. Also potentially useful to continuously monitor high risk areas (crossings, Road turns with poor visibility).</p>
Result	<ul style="list-style-type: none"> • <i>Qualitative</i>: Directly viewable material to humanly assess situations (even if blurred for data protection reasons). Flexibly deployable data collection, Flexible evaluation of road user movements. • <i>Quantitative</i>: Evaluation of effectiveness of other interventions. Potential to regulate traffic flows based on camera feedback at important points. Identification of conflict hotspots. • <i>Monetizable</i>: Reduction in crashes from placing of targeted measures. Reduced traffic flow disruptions through camera feedback on traffic movement.
Limitations	<p>Camera systems are limited in their field of vision. Automatic solutions require post-processing (object detection, tracking, deriving safety and traffic KPIs). Data protection is vital and not trivial. Camera solutions depend on a power supply, whether through the power grid or in the form of a battery.</p>
Relationships	<p>Linked with #2 Combining data sources to allow for quick evaluation (if acceptable for data protection), #5 Digital twins (providing examples of road user movements, or even near-real time traces), #7 system speed if evaluations are automated and #16 Risk mapping, if the relations of conflicts and road infrastructure are evaluated systematically to find risk spots in the camera area or on similar infrastructure</p>
Additional information	<p>In CAMBER, it could be useful for before-after analyses relating to road user behaviour. Real-time traffic management could be an intervention in itself. The incident detection aspect will be included via Mobile-Eye and is a valuable potential contributor of dynamic data.</p>

#2 – INTEGRATING AND VALIDATING MULTIPLE DATA SOURCES FOR CORRELATION, RELIABILITY, AND VALIDITY

Description	<p>Linking all available and relevant data sources used for road traffic, road safety and asset management. Redefining evaluation and performance criteria. We will establish the feasibility and, where possible, link data from at least the following sources 1) static/historic and live traffic data, static and dynamic road condition data (including from Flitsmeister or similar, see also Contextual information), road assets and associated data, weather data, road user data</p>
-------------	---

	and modelling data. The concept aims to improve data reliability and update frequency, enabling faster, data-driven decision-making and reducing the risk of late maintenance detection or overlooked safety issues.
Addressed Gap	Directly addresses knowledge and practice gaps related to data and models but with strong links to organisational, processes, technology Data interoperability and methodological transferability, particularly: <ul style="list-style-type: none"> • “Lack of data standardization” and “Fragmented and isolated systems” • “Integration complexity” in Digital Twins gaps.
CAMBER components	<ol style="list-style-type: none"> 1. Yes, these are vital data sources for RSM and RAM. 2. Yes, new generation data sources are being used. 3. Partially, data is a prerequisite for digital twins. 4. Partially, new (combined) data sources may improve identification of road quality issues that impact ADAS performance. 5. No.
Integration type	This solution covers interrelations between between all three systems involving data collection at the operational level and analysis and decision-making at the tactical level: {Operational in / Tactical, Operational in / Tactical, Operational in / Tactical}
Change	<ul style="list-style-type: none"> • Data enrichment; better management decisions; improved data quality standards, more efficient data collection and management, combining user reports, vehicle sensor data, and inspection records. • Correlating real-time inputs with verified ground-truth data. • Applying Signal Detection Theory (SDT) principles (true positives, misses, false alarms, false negatives) to quantify reliability and optimise accuracy vs. responsiveness. This shift allows authorities to rely on more frequent, verified data for both maintenance and safety operations, leading to earlier interventions and more efficient resource allocation.
Use cases	No specific use cases, relevant for site prioritisation and treatment, traffic management, maintenance programming, etc.
Result	<ul style="list-style-type: none"> • Data Standards and integration guidelines; dimensions and metrics for data grading; Integrated prioritisation procedures and processes for identifying interventions; improved reliability and confidence in real-time road condition data. • Potential KPIs: <ul style="list-style-type: none"> ○ True positive rate and false alarm rate (quantitative) ○ % of verified multi-source reports acted upon (quantitative) ○ Mean time between defect occurrence and intervention (quantitative) ○ Cost savings from earlier detection (quantitative, monetisable) ○ User engagement or satisfaction index (qualitative)
Limitations	Different definitions of data, incompatible formats or data platforms, unreliable sources, data ownership and willingness or ability to share/integrate, high upfront costs for system interoperability, risk of biased input from over- or underrepresented user groups.
Relationships	Links with all, except not so much 8 and 9
Additional information	This combined approach can be implemented through a modular architecture: <ol style="list-style-type: none"> 1. Data Ingestion Layer; Collects user; CVD, and inspection data.

	<ol style="list-style-type: none"> 2. Validation & Correlation Engine; Uses SDT and statistical methods to match and verify data. 3. Decision Layer; Feeds verified data into RAM/RSM systems and Digital Twins. 4. Early pilots could prioritise environments where existing data systems and reporting platforms already exist, ensuring manageable integration.
--	---

#3 – SPATIAL SPECIFICATION

Description	<p>Map features relevant to RSM and RAM into a common (spatial) frame of reference to easily explore interrelations and use features relevant to both. For instance, road condition properties might well be safety relevant via implied breaking distances or the presence of road surface damages. In turn, safety relevant data like vehicle movements/IMU data/floating vehicles data can be an indicator for predictive maintenance and thus contribute to RAM.</p> <p>The integration with digital twins necessitates the spatial specification and also provides the highest level of integration which can benefit simulations and evaluations of interventions for both RAM and RSM.</p>
Addressed Gap	<ul style="list-style-type: none"> • Lack of data standardization As the approach might force data into a common structure/graph/database • Fragmented and isolated systems As the approach is intended to put data into a common data ecosystem • Limited scalability of advanced tools As standardized data would be available on wider road network • Processing and infrastructure constraints As collection and synthesis could be managed by professionals beyond the regional level
CAMBER components	<ol style="list-style-type: none"> 1. Yes, the joint representation would allow for quick association of safety and maintenance measures and 2. Partially. This solution is more about integrating and standardising existing sources 3. Partially, as this sort of data integration should be part of and available in a local digital twin 4. Partially, as the information in the spatial frame could contain relevant information for CCAM/ADAS operation (speed limits, traffic, infrastructure properties) 5. Partially. Traffic, safety and infrastructure data may help guide the deployment of interventions.
Integration type	<p>This solution addresses the tactical and strategic level to enable new operations and evaluations.</p> <p>{Strategic / Tactical, Strategic / Tactical , Strategic / Tactical }</p>
Change	<p>Enables more systemwide optimisation through accurate representation of road condition, road inventory and potentially safety relevant features in combination with event data, vehicle dynamics and other dynamic data. Allows</p>

	for fast responses to events and road conditions through accurate assessment and localization.
Use cases	Natural component of a digital twin. More widely an example of how data from the worlds of safety and road asset management can be brought together and made available to road authorities. Can enable systematic studies of risk.
Result	<ul style="list-style-type: none"> • <i>Qualitative</i>: Detection of interdependent issues of road maintenance and road safety. • <i>Quantitative</i>: Detection of problem hot spots, Detection of trends (safety and maintenance issues increasing), Dynamic data allowing to localise issues early, more safety through good road conditions • <i>Monetizable</i>: Fewer crashes due to infrastructure being maintained earlier, fewer necessary measures due to accurate localisation of safety and maintenance issues and available knowledge of the surrounding infrastructure.
Limitations	Building the common data source is an extensive effort and information needs to be updated frequently. Proper sensor solutions need to be identified to update continuously and procedures for combining RSM and RAM data need to be in place.
Relationships	#16 Risk mapping can include features of RAM too and would ideally operate within this framework. #5 Digital Twins requires this to be locally implemented in a sense.
Additional information	For the digital twin building in CAMBER this needs to be performed. For the wider road network, this is a desirable effort, in a not as detailed fashion, to empower road authorities and researchers both to work with accurate reflections of the situation on the road. This is pursued in several countries (see for instance the Austrian GIP)

#4 – DATA / METRICS DICTIONARY

Description	<p>This idea focuses on improving the quality, consistency, and usability of infrastructure and safety-related data by developing standardised metrics and integrating novel data sources into road safety and asset management practices.</p> <p>The approach promotes a more proactive safety management model through the creation of clear, data-driven indicators supported by emerging sources such as crowdsourced pavement condition and driving events data. Furthermore, it aims to enhance the relationship between traditional road infrastructure condition indicators and new data-generated indicators, thereby enabling a more comprehensive and evidence-based understanding of road performance and safety conditions. Relating novel indicators to those currently used facilitates a smooth transition from traditional practices to digital RSM and RAM frameworks.</p>
Addressed Gap	Addresses the lack of data standardisation in RAM and RSM, while also improving data quality and availability.

CAMBER components	<ol style="list-style-type: none"> 1. Yes, common metadata structure is key to integration 2. Yes, new generation data sources are needed to define new indicators 3. Yes, common variable and indicators definitions are required for DT implementation. For DT to be bidirectionally active, V2x and novel data sources are needed. 4. Yes, CCAM provides the platform for novel data to be accessed and shared; ADAS performance can be linked to new performance and condition indicators and these need to be related to standardised specifications for procurement. 5. Partially, as new data for exposure is envisioned; and in due time, as experience allows relating the new variables with crash frequencies.
Integration type	<p>This solution is relevant for all three systems, both at the tactical and operational input levels</p> <p>{Operational in / Tactical, Operational in / Tactical, Operational in / Tactical}</p>
Change	<ul style="list-style-type: none"> • Improved data interoperability and reliability across sectors, as a result of establishing common data standards for collecting and managing infrastructure, traffic and safety-related information and improving consistency across authorities and systems. Enhancing data interoperability facilitates the integration of information from multiple sources, such as RAM, RISM, and CCAM technologies. • Allows shifting safety and asset management from reactive to proactive, enabling earlier detection of potential risks or condition deterioration and faster interventions. • Introduces clear and measurable safety and asset performance indicators derived from real-time and crowdsourced data. • Swifter detection of performance safety-related degradations. • Allows for linking traditional infrastructure indicators (e.g. pavement distress, skid resistance) with new data-driven insights (e.g. vehicle sensor or crowdsourced data). • Promotes data sharing across agencies, encouraging cooperation between road authorities, researchers, and industry. • Reduces data silos and fosters joint innovation in predictive safety and asset management tools.
Use cases	Relevant to pilot sites with dense networks, prone to sudden changes in traffic or land use characteristics.
Result	<ul style="list-style-type: none"> • Qualitative: standardised data ecosystem, integrated management, and evidence-based safety culture. • Quantitative: increase in the number of datasets standardised across participating authorities, increase in data accessibility (real-time safety and maintenance data available to operational teams). • Monetizable: efficiency gains from reduced data handling.
Limitations	<ul style="list-style-type: none"> • Inconsistent triggering criteria for flagging relevant events, and data formats: Differences between authorities, vehicle manufacturers, sensor models, or data platforms can complicate integration. • Environmental conditions, hardware failures, or incorrect calibration can affect repeatability and reproducibility of measurements, and data accuracy
Relationships	Linked with #12 (CCAM as mobile sensors), #13 (Crash-data informed RSM decisions) and #14 (Safety measures during maintenance).

Additional information	-
------------------------	---

#5 – DIGITAL TWINS: VALUE & REQUIREMENTS

Description	<p>This idea defines how DTs can add practical value to existing road asset and safety management systems. Many road authorities already use partial models, so the DT's value must be clear, targeted, and flexible. The approach promotes modular, switchable functionalities. This enables DTs to operate at varying levels of detail and integration, depending on the availability of data and user needs.</p> <p>DTs can be employed in different phases of the road network life cycle, including planning and design, construction and completion, operation and maintenance, and demolition and reconstruction (Yan et al., 2025). In addition, contributions to road traffic management aspects can also be expected through the implementation of a digital twin (e.g., Aloupogianni et al., 2024; Kamal et al., 2024).</p>
Addressed Gap	<ul style="list-style-type: none"> • Lack of standardization and universal frameworks • Limited data for training – Synthesized data can be achieved through digital twin for training models • Data quality, availability, and heterogeneity
CAMBER components	<ol style="list-style-type: none"> 1. Partially. The DT contributes to improving the quality and timeliness of safety- and maintenance-relevant information, and can even be used to define specific procedures. 2. Yes. DTs rely on real-time feeds from probe vehicles, smartphone telemetry, sensors, and camera/LiDAR data, making them strong users of next-generation inputs. 3. Yes. This solution is centred on establishing DT concepts, value propositions, and operational requirements. 4. Yes. DTs can incorporate visibility, signage, marking, and geometry attributes relevant for ADAS functioning. 5. No. The solution does not introduce or modify physical low-cost interventions.
Integration type	<p>This solution strengthens mid-level planning by enabling more systematic prioritisation within RAM and RSM. If DTs support traffic management simulations, tactical-level integration across all three systems emerges. It does not directly influence operational execution unless modules are activated at the operational level.</p> <p>{Tactical, X, Tactical}, or {Tactical, Tactical, Tactical} when including traffic management.</p>
Change	<p>Introduces adaptive integration between existing RAM and RSM systems through configurable modules. This enhances interoperability without enforcing a single DT structure and improves usability, scalability, and acceptance by road authorities.</p>
Use cases	<p>Applicable to pilot sites adopting DT-based RSM and RAM. Use cases include surface condition monitoring, asset condition detection, and predictive maintenance prioritisation.</p>
Result	<ul style="list-style-type: none"> • <i>Qualitative</i>: higher user acceptance, transparency, and trust in DT tools.

	<ul style="list-style-type: none"> • <i>Quantitative</i>: number of active DT modules deployed (switchable on/off controls), reduction in redundant data collection, and increased update frequency of road-condition indicators. • <i>Monetizable</i>: efficiency gains from reduced inspection costs and optimised maintenance cycles.
Limitations	Implementation may be limited by non-standardised data formats and data-sharing barriers across authorities. Costs primarily relate to initial data integration, staff training, and development of the DT module.
Relationships	Linked with #2 (Combined Data Sources) and #4 (Data / Metrics Dictionary), which supply interoperable data foundations. Supports #9 (Interdisciplinary CBA) by providing quantitative input for value assessment. Linked with #14 and #16, provided that the extension to DT is considered viable for these ideas.
Additional information	Highly relevant for pilot sites already using digital twins. A step-by-step deployment, maybe from DTs focused on maintenance toward full integration with RSM. This will strengthen scalability and stakeholder confidence. The concept aligns with WP4 objectives on “solution investigation and digital twins.”

#6 – ORGANISATIONAL INTEGRATION OF ROAD ASSET AND ROAD SAFETY MANAGEMENT

Description	A perception exists that a number of functions within road authorities structures make use of similar data sources but for different purposes. The responsibilities of these departments are very different, although it may be feasible and more efficient if there was better coordination, possibly even integration, of responsibilities and functions. If integration is not possible, at least achieve better coordination between RA, RT and RS management departments to improve more efficient use of resources and greater effect on traffic management and safety.
Addressed gap	The primary gap addressed is at the organisational level but also related to processes.
CAMBER components	<ol style="list-style-type: none"> 1. Yes, streamlining the management functions within the organisation leads to improved coordination and efficiency 2. Yes, making use of data from new sources 3. Yes, DT form the platform with which management decisions are made 4. Partially, utilise CCAM information to improve data provisions to these platforms and assess efficacy 5. Yes, management decisions are made to decide on interventions.
Integration type	Strategic-Tactical across RTM, RSM, and RAM, as well as Strategic-Tactical-Operational within each of these systems. {Strategic /Tactical, Strategic / Tactical, Strategic /Tactical}
Change	<ul style="list-style-type: none"> • From independant RSM, RTM and RAM interventions to coordinated and integrated planning and prioritisation of interventions for all three. Within each, more efficient and targeted interventions, dominant shift from reactive to proactive • Quantitative direct: Reduced manpower inputs; reduced maintenance costs (less failures) • Quantitative indirect: Reduced crashes; reduced congestion, less IM

	<ul style="list-style-type: none"> Qualitative: Higher road user satisfaction; greater employee satisfaction.
Use cases	No specific use case but best applicable in Pilot sites with uncoordinated structures
Result	More efficient use of resources (both manpower and equipment/furniture/maintenance), reduced backlogs, fewer high-risk locations
Limitations	Functions and responsibilities cannot be practically integrated because of data restriction/access and or personnel regulations/labour laws
Relationships	Essentially with all clusters (solutions #1-7).
Additional information	Highly relevant to all pilot sites, particularly to demonstrate how RSM and RAM can be more efficiently managed.

#7 – SYSTEM SPEED

Description	This idea is for the development a <i>lightweight data-exchange layer</i> between RSM and RAM systems that identifies and shares only essential subsets of data needed for cross-functional decision-making. This ensures that integration enhances coordination without slowing system performance. The layer can also support configurable <i>decision-making scenarios</i> to adapt risk reporting and intervention proposals to each authority's speed and policy context.
Addressed gap(s)	Addresses gaps in data interoperability, decision-making latency, and institutional coordination (see D2.1 section 4.7).
CAMBER components	<ol style="list-style-type: none"> Yes, this functionality is important for integration of these systems Partial, because it affects the speed of data exchange and the volume of data transferred Partial, for interoperability of the digital twins No No
Integration type	Operational across RTM, RSM, and RAM. {Operational_in, Operational_in, Operational_in}
Change	Shift from siloed RSM/RAM workflows to selective, automated data sharing through a configurable interface. This enables faster, context-aware decision support and reduces manual coordination across departments.
Use cases	Applies to project planning, prioritisation of maintenance and safety interventions, and performance tracking across multiple departments or agencies. Applicable to Cascais – Need to confirm with MobiCascais and Municipality if scenarios may be identified. (The relation with automated risk reporting is not fully understood)
Result	<ul style="list-style-type: none"> Quantitative: reduction in data retrieval and processing time (e.g. >30%); increased alignment of project plans (number of coordinated interventions); faster decision-making cycles (e.g. mean days to action). Qualitative: improved perceived usability and inter-departmental collaboration.
Limitations	Requires initial mapping of common data schemas and agreements on data-sharing protocols. May face institutional resistance or require policy alignment.

Relationships	Depends on #2 (Combining Data Sources) and #6 (Social Integration) for data and organisational alignment. Enables: Supports #4 (Data/Metrics Dictionary), #9 (Interdisciplinary CBA), and #16 (Crash Prediction) through faster, standardised data exchange.
Additional information	Applicable to pilot sites with existing but siloed data infrastructures (e.g. where both RSM and RAM systems are in place). In settings with lower digital maturity, implementation may focus first on defining minimal shared data elements before automation.

#8 – CURVE PARAMETERS

Description	Share curvature and curve quality parameters (e.g. radius, delineation, CAMBER) from RSM systems with the road safety analysis team. These data directly inform iRAP risk models, where sharper or poorly delineated curves significantly increase crash risk for vehicle occupants, motorcyclists, and cyclists. Integrating such data enables more precise network risk mapping and prioritisation of high-risk curves.
Addressed gap(s)	Addresses D2.1 gaps on data granularity and transfer between asset management and safety modelling (sections 3.4 and 4.7). Supports improved representation of geometric features in safety assessments.
CAMBER components	<ol style="list-style-type: none"> 1. Yes, this data is directly used within the Safety assessments 2. Yes, this can come from new-generation data sources 3. Yes, this is a road characteristic that could be integrated into digital twins 4. Yes, this is a road characteristic that could impact the performance of CCAM/ADAS 5. No
Integration type	Tactical in RSM, Operational in RAM, and no impact on RTM. {Tactical, X, Operational in}
Change	Enhanced data exchange between maintenance (RSM) and safety (RAM) domains to include curve geometry parameters and delineation ratings, enabling risk-sensitive maintenance prioritisation.
Use cases	Curve resurfacing and delineation programmes; identification of high-risk curves for signage, speed management, or guardrail upgrades.
Result	<ul style="list-style-type: none"> • Quantitative: Improved accuracy of risk estimates (e.g. reduction in uncertainty bands for curve-related FSI predictions); more targeted interventions at high-risk curves (measured as proportion of curve-related FSI addressed). • Qualitative: Improved communication between engineering and safety teams, and evidence-based prioritisation of geometric improvements.
Limitations	Requires calibration of RSM curve data to align with iRAP category thresholds (e.g. radius <200 m, 200–500 m, etc.). Some curve-quality parameters (e.g. delineation) may be subjective or inconsistently recorded.
Relationships	Dependencies: #2 (Combining Data Sources), #3 (Spatial Specification), #4 (Data/Metrics Dictionary). Enables: #16 (Crash Prediction) and #5 (Digital Twins) through improved geometric data accuracy.
Additional information	Applicable where RSM systems already record geometric parameters from survey vehicles or LiDAR. The shared data can feed directly into iRAP model parameters on “Curvature” and “Quality of Curve”

#9 – INTERDISCIPLINARY CBA: FRAMEWORK FOR EVALUATING THE INTEGRATED VALUE OF NOVEL DATA SOURCES

Description	This idea proposes developing a structured framework to assess the costs and benefits of novel data sources, such as connected vehicle and across all relevant domains/systems (RSM, RTM, RAM). The goal is to shift from evaluating each data source in isolation, and instead measure its holistic value in supporting integrated, data-driven road management.
Addressed gap(s)	Validation and generalisability of models and cost-benefit frameworks, particularly: <ul style="list-style-type: none"> • “Limited research on automation of data fusion... consistency of data standards... uncertainty on how CAVs will impact asset management and KPIs.” • “Evaluation practices are weak, as most authorities do not systematically evaluate the effectiveness of interventions.”
CAMBER components	<ol style="list-style-type: none"> 1. Yes – the idea has the benefit of better integration 2. Yes – the idea is all about novel sources 3. Partial – sources could support digital infrastructure and real time tracking 4. Partial – benefits assessed for new data sources may relate to ADAS performance, for example 5. No
Integration type	This solution covers interrelations between all three systems, focussed on decision-making at the tactical level: {Tactical, Tactical, Tactical}
Change	Shift the focus from fragmented, purpose-based evaluations to a comprehensive, multi-domain cost–benefit methodology. This change enables authorities to make evidence-based investment decisions in data acquisition and management, considering benefits that span multiple departments (e.g. improved maintenance efficiency and enhanced safety monitoring).
Use cases	<ul style="list-style-type: none"> • Comparing performance of traditional vs. new-generation data for the same use cases. • Evaluating return on investment (ROI) for new data partnerships.
Result	<ul style="list-style-type: none"> • Share data more efficiently • Make better use of limited budgets • See the full value of the data across different areas • Better coordination between departments • Stronger justification for investment and integration of new data streams. • Potential KPIs: <ul style="list-style-type: none"> ◦ Reduction in duplication of data purchases (quantitative, monetisable) ◦ Net benefit ratio for shared data use which compares the value gained from using shared data (e.g. improved safety or cost saving) to its cost (data acquisition, system upgrades, staff training) (quantitative, monetisable).
Limitations	<ul style="list-style-type: none"> • Complex to allocate benefits across departments.

	<ul style="list-style-type: none"> • Potential confidentiality and cost-sharing issues with private data providers.
Relationships	<ul style="list-style-type: none"> • Depends on ideas #2 and #3, as sources to be evaluated. • Enables strategic decisions on data investments and system integration. • Supports idea #4, by identifying which data sources best support proactive safety metrics
Additional information	This framework can build on existing cost-benefit approaches from other projects and expanding them to include operational and safety benefits jointly.

#10 – WORK ZONES

Description	Digital information related to work zones – such as precise location, geometry, duration and dynamic status (e.g. lane closures, reduced speed limits or worker presence) – can be used to enhance road safety. When shared in real-time with connected vehicles, infrastructure systems and navigation services, this information enables early warnings, automated vehicle adaptation and optimized traffic management around work zones. This reduces risks for both road users and workers by improving awareness, predictability and reaction time in complex temporary traffic situations.
Addressed gap	Work zones address primarily the gaps related to processes, data and technology
CAMBER components	<ol style="list-style-type: none"> 1. Yes, asset maintenance activities are anticipated to be integrated with safety management. 2. Yes, telematics are used to facilitate smooth traffic flows around worksites. 3. Partially, Digital Twins could be used to oversee the maintenance activity and to direct traffic flows. 4. Yes, adaptation of vehicle automation based on changes in the road due to construction work is a central aspect of this solution. 5. No, although work zones may be set up to implement interventions, this solution does not concern the actual interventions.
Integration type	Data is being collected from vehicles (road traffic management system, operational input), which are used to inform decision-making at the tactical levels (safety and asset management systems), which in turn are used to inform road users at the operational output level (road safety and road traffic management systems). {Operational_out / Tactical, Operational_in / Operational_out, Tactical}
Change	Ensures that safety critical temporary changes to available road structure are accurately reflected on the digital road representation and communicated to digital systems of approaching vehicles.
Use cases	Relevant to pilot sites but also as a demonstrator of proactive traffic and safety management. Relevant to specifically real time road user information provision. Ensures that assistance systems and CCAM solutions remain accurately operable whilst temporary works are performed on the road. Digital connection and communication to vehicles could allow for smoother traffic flows around worksites.
Result	Improved road user behaviour in and around work zones

	<ul style="list-style-type: none"> • <i>Qualitative</i>: A safe environment for road workers and for approaching vehicles using assistant systems of various levels. • <i>Quantitative</i>: Reductions in unsafe interactions around work zones. More automation systems operable in work zones. Fewer and shorter traffic jams around workzones. • <i>Monetizable</i>: Reduction in crashes around work zones. Less disruption to traffic flows.
Limitations	Effect is driven by the population of motorists reached with the additional information and their reaction and interpretation of the information provided An obvious further limitation is that all measures related to this idea are limited in effect to given work zones and thus their netwide impact might vary.
Relationships	Linked with #5 Digital twins (providing up to date information on road segments that temporarily have a different structure and are subject to different rules). Also links with #2 and #11 and #4, and #14
Additional information	Very relevant to CCAM as the road layout and driving rules around a worksite can vary and deviate significantly from the usual situation at the respective road segment.

#11 – LOCATION-BASED PROBING: MAPPING THE SPREAD OF DETECTED PROBLEMS THROUGH TARGETED USER PROBING

Description	This idea suggests actively probing road users near a detected problem to determine whether the issue also exists beyond the initial location, effectively mapping the spatial spread or recurrence of road problems. By asking targeted users in the vicinity about the same issue, the system can confirm if a local defect has network-level implications.
Addressed gap(s)	Technical and representational, and inclusion of secondary roads and underrepresented users, particularly: “Data sparsity in rural areas and for vulnerable road users.” “Monitoring tends to focus on car traffic and higher-order roads... limited insight into secondary roads.”
CAMBER components	<ol style="list-style-type: none"> 1. Yes – support for RAM and RSM decision making 2. Yes – this is a novel collection method 3. Partial – information could be integrated into DT 4. No 5. Partial – likely focussed on infrastructure condition
Integration type	This solution involves the collection of asset condition data to inform decision making at the tactical level across all three domains. {Tactical, Tactical, Operational_in / Tactical}
Change	Adds a dynamic feedback mechanism to expand from local detection to network-level diagnosis. The system uses targeted, crowdsourced confirmation (asking nearby drivers if “issue X” is observed at position Y+d).
Use cases	<ul style="list-style-type: none"> • Checking if potholes, roughness, or faded markings extend along a corridor. • Confirming if flooding or debris persists beyond the initial report area. • Assessing the effectiveness of repairs.
Result	<ul style="list-style-type: none"> • Better understanding of how road issues spread spatially. • Enables prioritisation of maintenance zones rather than single spots. • Supports network-level performance monitoring.

	<ul style="list-style-type: none"> • Potential KPI: % of confirmed extensions of detected issues (quantitative).
Limitations	<ul style="list-style-type: none"> • Requires real-time communication or app notification capability. • Risk of low user participation or inaccurate feedback.
Relationships	<ul style="list-style-type: none"> • Linked to Idea #2, builds on user-generated reports and feedback validation mechanisms. • Supports Idea #4, contributes to proactive safety metrics by identifying issue spread. • Complementary to Idea #2 and #9, can leverage connected vehicle data and benefit from integrated data evaluation. • Enabled by Idea #3, requires standardised spatial data for accurate mapping and probing.
Additional information	Probing frequency and radius can be adaptive based on traffic density and report confidence.

#12 – CCAM AS MOBILE SENSORS

Description	<p>This idea focuses on leveraging vehicles equipped with CCAM technologies as mobile sensors that continuously collect data on road conditions, traffic flow, and driver behaviour. These data can be integrated with information from RSUs.</p> <p>These data streams enable a transition from traditional, reactive scheduled maintenance to dynamic, data-driven asset management. Using ML and big data analytics, it becomes possible to identify crash hotspots, predict potential risks, and guide smarter infrastructure investment decisions.</p>
Addressed Gap	Addresses sensing limitations, data sparsity in rural areas and a lack of focus on VRU, modal and temporal underrepresentation, and the lack of behavioural data, increasing data availability and completeness.
CAMBER components	<ol style="list-style-type: none"> 1. Yes. these are vital data sources for RSM and RAM. 2. Yes. These are new generation data sources. 3. Partially, these data allow for more frequent assessment of road condition and safety level evaluations. 4. Yes. ADAS availability is directly measured with these sensors. 5. Partially, dependent on relationships with traditional performance indicators.
Integration type	<p>CCAM mobile sensor data potentially covers a wide range of variables relevant to supporting decision-making at tactical levels. Depending on successful correlation with traditional performance indicators and experience, these data are promising at the operational input level as well.</p> <p>{Operational_in / Tactical, Operational_in / Tactical, Operational_in / Tactical}</p>
Change	<ul style="list-style-type: none"> • Shifting from reactive or scheduled maintenance to predictive, data-driven management reduces costs and response time to maintenance issues. • Enabling early identification of crash hotspots and high-risk areas, allowing for targeted interventions and safer road designs. • Providing real-time insights into traffic flow that can optimise traffic management, reduce congestion, and improve travel times.

	<ul style="list-style-type: none"> • Giving road authorities evidence-based tools to prioritise infrastructure investments and allocate resources effectively.
Use cases	Relevant to pilot sites with dense networks, prone to sudden changes in traffic or land use characteristics.
Result	<ul style="list-style-type: none"> • Qualitative: smarter decision-making, promotion of proactive safety measures, and operational efficiency. • Quantitative: reduction in reactive road maintenance, decrease in traffic congestion, reduction in crash frequency, and improved asset lifespan. • Monetizable: efficiency gains from reduced maintenance costs, accident cost savings, and reduced traffic delays. Reduction in periodic inspections.
Limitations	<ul style="list-style-type: none"> • Inconsistent triggering criteria for flagging relevant events and data formats. Differences between authorities, vehicle manufacturers (and firmware updates), or data platforms can complicate integration. • Environmental conditions, hardware failures, or incorrect calibration can affect the repeatability and reproducibility of measurements and data accuracy • Implementation may be limited by data quality and standardisation (inconsistent data formats and sensors' reliability). • Privacy and data security concerns (including personal data protection and cybersecurity risks). • Costs primarily relate to deploying RSUs, upgrading digital infrastructure, and setting up data platforms.
Relationships	Linked with #4 (Data/metrics dictionary), #13 (Crash-data informed RSM decisions) and #14 (Safety measures during maintenance).
Additional information	Especially useful for pilot sites testing safety-integrated maintenance strategies. Supports CAMBER's objectives in WP5 (Pilot Testing and Evaluation) by combining maintenance scheduling with safety measures.

#13 – CRASH-DATA INFORMED RSM DECISIONS

Description	This idea focuses on transforming the traditionally reactive approach to asset management, which currently relies on public complaints and staff engineering judgment. While strategic Road Asset Management (RAM) decisions typically address annual maintenance budgets and large-scale maintenance projects, and Road Safety Management (RSM) decisions often draw on accident data, such information is not readily accessible at the operational level.
Addressed Gap	Addresses the methodological issues in the development of KPI and the integration challenges
CAMBER components	<ol style="list-style-type: none"> 1. Yes, as it involves the development of road safety and asset performance indicators. 2. Yes, new generation data sources are used. 3. Partially, data is a prerequisite for digital twins. Proactive decision-making is key for process twins (see Table 27, D2.1). 4. No. 5. Partially. CAMBER will select a group of candidate low-cost interventions suited to the selected locations in the pilot sites.

Integration type	This solution involves shifting to a proactive approach, considering road safety indicators as well. It is relevant for the safety and asset dimensions. {Tactical / Operational_in, X, Tactical}
Change	<ul style="list-style-type: none"> • Replaces subjective engineering and citizens' judgment by objective, real data (eventually real-time data from connected vehicles and sensors). • Bridges the gap between asset condition data and safety performance data, allowing coordinated planning. • Reduces the time spent on manual inspections and data collection. • Enables data-supported justification for maintenance budgets and investment decisions.
Use cases	Relevant to pilot sites with dense networks, prone to sudden changes in traffic or land use characteristics.
Result	<ul style="list-style-type: none"> • Qualitative: decisions based on measurable data, promotion of proactive safety measures and asset maintenance, and operational efficiency. • Quantitative: reduction in reactive road maintenance, decrease in inspection time, improved access to operational safety data, and improved asset lifespan. • Monetizable: efficiency gains from reduced maintenance costs, reduced inspection and administrative times, accident cost savings, and reduced traffic delays.
Limitations	Implementation may be limited by data quality and standardisation (inconsistent data formats and sensors' reliability), as well as privacy data concerns (including personal data protection). Shifting from experience-based decisions to data-driven processes demands specialized training and can meet internal resistance.
Relationships	Linked with #4 (Data/metrics dictionary), #12 (CCAM as mobile sensors) and #14 (Safety measures during maintenance).
Additional information	

#14 – SAFETY MEASURES DURING MAINTENANCE

Description	The idea focuses on integrating proactive safety measures into road maintenance throughout its lifecycle, using real-time monitoring and predictive analytics. It aims to identify and mitigate temporary risks caused by roadworks (which can be implemented through dynamic traffic management, intelligent signage, and feedback from connected vehicles or sensors). In addition, this idea can be expanded, and maintenance-based DTs can also be employed to predict the correct time for predictive maintenance of the road network.
Addressed Gap	<ul style="list-style-type: none"> • Shifting from Reactive to Predictive Maintenance: The current approach to maintenance is largely reactive, which results in interventions being more extensive and expensive because they occur only after visible damage occurred. • Integrating Safety and Managing Dynamic Risks: A significant organizational gap is that road safety is often overlooked in maintenance

	<p>prioritisation, illustrating a lack of integrated decision-making between asset and safety.</p> <ul style="list-style-type: none"> • Adopting Advanced Digital Twins and Real-Time Data: Road management is hindered by the lack of comprehensive, high-quality data systems to support data-driven management.
CAMBER components	<ol style="list-style-type: none"> 1. Yes. The solution embeds safety explicitly within maintenance operations and planning. 2. Partially. Real-time data from connected vehicles, sensors, and predictive analytics supports deployment, but not all use cases require advanced data inputs. 3. Partially. DTs can provide predictive maintenance and dynamic risk identification, but using DTs is an enhancement rather than a prerequisite. 4. Partially. Dynamic signage, variable warnings, and improved predictability of temporary work zones support ADAS operability, though impacts depend on implementation. 5. Yes. Dynamic and temporary measures (e.g. variable limits, temporary markings, work-zone signage) fall directly under low-cost interventions.
Integration type	<p>Operational decisions (e.g. deployment of safety measures during works) link with tactical coordination in traffic and asset management. It enhances how maintenance works are planned (tactical) and how safety protocols are implemented (operational_out). It does not fundamentally alter strategic planning.</p> <p>{Operational_out, Tactical, Tactical}</p>
Change	<p>Shifts maintenance planning from a reactive to a proactive approach. This enables the predictive identification of high-risk conditions (e.g. work zones, partial closures) and the automatic deployment of adaptive safety measures, such as variable speed limits or warning systems.</p>
Use cases	<p>Relevant to pilot sites conducting frequent maintenance on mixed-traffic urban or secondary roads. Typical use cases include resurfacing operations, utility repairs, or short-term lane closures where safety risks fluctuate dynamically.</p>
Result	<ul style="list-style-type: none"> • <i>Qualitative:</i> improved road-user safety perception, enhanced coordination between maintenance teams and road authorities. • <i>Quantitative:</i> reduced number of work-zone related incidents, shorter response times for hazard detection, improved compliance with safety protocols. • <i>Monetizable:</i> savings from reduced crash-related costs, minimised disruptions, and lower insurance or compensation claims.
Limitations	<p>Implementation depends on sensor coverage, connectivity infrastructure, and access to real-time data feeds. Costs may arise from system integration and equipment maintenance.</p>
Relationships	<p>Linked with #5 (Digital Twins: Value & Requirements) and #7 (System Speed), which support real-time data exchange and adaptive response. Also complements #12 (CCAM as Mobile Sensors) by leveraging connected vehicles for work-zone safety monitoring.</p>
Additional information	<p>Especially useful for pilot sites testing safety-integrated maintenance strategies. Supports CAMBER's objectives in WP4 (Solutions Investigation and Digital Twins) and WP5 (Pilot Testing and Evaluation) by combining</p>

	maintenance scheduling with safety measures. It could evolve into a standard operational protocol for predictive maintenance and safety management.
--	---

#15 – CONTRACT STATUS

Description	<p>This idea proposes focusing primarily on existing contracts and integrating safety and data-sharing obligations into existing maintenance and service contracts to minimise excessive administrative stages and bureaucracy. Changing existing contracts to include new terms of reference or conditions may be challenging in some instances, but should be pursued nonetheless. This solution should therefore also focus on all new contracts. Terms and conditions covering activities related to the integration of asset, safety (and if necessary, traffic) management can be included as standard items in new contracts.</p> <p>It also highlights the importance of considering the contractual and administrative context when selecting and implementing interventions, which can correspond to RSM and RAM. The legal status of an intervention, whether it falls under an active contract or requires a new process, can significantly affect the time-to-implementation and overall cost. Differentiating between single and framework contracts helps improve planning efficiency and cost forecasting.</p>
Addressed Gap	<ul style="list-style-type: none"> • It minimises excessive administrative stages and bureaucracy by integrating safety and data-sharing into existing maintenance contracts, addressing organizational issues like siloed management and poor policy execution that typically delay interventions. • It tackles inadequate planning and cost management by emphasizing the contractual context when selecting interventions (RSM and RAM). • It resolves the gap where road safety is often overlooked in maintenance prioritisation by making safety and data-sharing requirements legally binding within contracts.
CAMBER components	<ol style="list-style-type: none"> 1. Yes. Embedding safety obligations into existing contracts directly strengthens safety-integrated maintenance procedures. 2. No. This solution does not introduce new data, though it may later require data-sharing clauses. 3. Partially. Contractual information can be incorporated into DTs for planning purposes, but DTs are not central to the solution. 4. No. There is no direct effect on CCAM/ADAS unless contract clauses indirectly affect asset quality. 5. Yes. Contract status affects the feasibility and timing of implementing low-cost interventions.
Integration type	<p>Contract structures influence planning decisions in RAM and RSM (tactical level) and determine which interventions can be executed without new procurement (operational_out). There is no direct strategic-level impact, and traffic management is only indirectly affected.</p> <p>{Tactical, X, Tactical}</p>
Change	<p>Introduces awareness of the contract status into the decision-support and intervention-selection process. Enables the evaluation framework to consider the presence of active or framework contracts as a separate indicator. This will</p>

	allow faster deployment of feasible interventions and more accurate scheduling of new ones.
Use cases	Relevant to pilot sites collaborating with multiple subcontractors or local agencies. Use cases include road resurfacing, inspection outsourcing, and data updates for DTs linked to contract performance.
Result	<ul style="list-style-type: none"> • <i>Qualitative</i>: improved planning transparency, better coordination between engineering and administrative teams. • <i>Quantitative</i>: reduced average time-to-implementation, fewer administrative delays, and lower initial setup costs for contract-covered interventions. • <i>Monetizable</i>: cost savings from reduced procurement efforts and faster safety improvements.
Limitations	Dependent on the availability and accessibility of contract databases. Variability in legal and administrative procedures across countries can limit the comparability of results. Updates to contract terms may require manual verification or inputs from local authorities.
Relationships	Linked with #5 (Digital Twins: Value & Requirements) for integrating contract data layers into DT environments, and with #14 (Safety Measures During Maintenance) since active contracts often define the safety obligations during roadworks. Supports #9 (Interdisciplinary CBA) by incorporating administrative cost factors into benefit-cost estimation.
Additional information	Considering contract status within the evaluation framework enhances the practical feasibility assessment of interventions. The differentiation between single and framework contracts helps identify measures suitable for immediate implementation. This contributes to a more realistic deployment strategy during pilot testing and later replication phases.

#16 – CRASH PREDICTION AND RISK MODELLING

Description	<p>Risk mapping based on localized road user movements data and crash data can be a new means to improve road safety proactively. Given the potential of floating vehicle's data, there might be considerable statistical power available to localize and deal with risk spots on the road infrastructure, based on risk model calibrated to real (or in principle also simulated) crash data. Such a methodology could also be applied to road maintenance aspects, provided indicators of road condition deterioration are obtained and the relation to floating vehicles data is explored.</p> <p>Provided a digital twin of the area in question has been set up, even more complex interactions with the road environment could be investigated.</p>
Addressed Gap	New Solution
CAMBER components	<ol style="list-style-type: none"> 1. Partially, through the possibility of associating infrastructure data and crash/conflict events 2. Yes, in particular the generation of model data from vehicle dynamics measurements (or CAN bus data) qualifies 3. Partially, as the risk estimates can be integrated 4. Yes, as the risk estimates can be made available and be useful for adapted/intelligent CCAM/ADAS.

	5. No, currently, this solution is based on probe vehicle data or floating vehicles data; when the automotive/vehicle sector is establishing more advanced CCAM/ADAS solutions, the prize will drop quickly.
Integration type	This solution addresses the tactical level of road safety management. Potentially also the tactical levels of the other two components. {Tactical, Tactical, Tactical}
Change	Risk mapping can proactively provide risk spots anywhere that sufficient floating vehicles data or probe vehicle data is available. If data from the in-vehicle CAN-Bus were widely used (anonymized), then frequent safety assessments of the roads would be possible.
Use cases	Detecting risk spots proactively, in particular for vulnerable road users (motorcyclists). With floating vehicle's data: Monitor continuously for risky spots.
Result	<ul style="list-style-type: none"> • <i>Qualitative</i>: Focus points for safety investigations/assessments. • <i>Quantitative</i>: fewer safety incidents, in particular for vulnerable road users. • <i>Monetizable</i>: savings from reduced crash-related costs, minimised disruptions, and lower insurance or compensation claims.
Limitations	<ul style="list-style-type: none"> • Requires probe vehicle data or floating vehicle's data on the roads of interest. • Requires enough data for a robust estimate.
Relationships	#3 Spatial specification as it is a mapping technique and could be combined with RAM data, #5 as it can be included in a digital twin. #13 (CCAM as mobile sensors) can be processed to become #16 too, for the respective vehicle type.
Additional information	Measurements with the Motorcycle Probe Vehicle are planned on multiple locations in CAMBER and other floating vehicles data is expected to become available, allowing for in-depth investigations into this.

ANNEX 2: LOW-COST SAFETY INTERVENTIONS

A template was used to consistently and systematically review each of 30 interventions identified through co-creation in T4.1. The result of the review for each of the shortlisted 30 low-cost interventions is shown in the following tables:

#1: MINI-ROUNDABOUTS

Mini roundabout: A mini roundabout is a small, often mountable circular intersection treatment designed to manage vehicle conflicts and reduce approach speeds. It typically replaces stop- or yield-controlled intersections in constrained urban environments, using a compact central island (generally of less than 4m diameter) that drivers can overrun if necessary while still enforcing deflection and slowing.

Summary of Evidence Base

Mini-roundabouts are compact circular intersections designed to manage vehicle conflicts and reduce speeds. Evidence (Elvik et al., 2009; SafetyCube) indicates consistent reductions in vehicle-vehicle injury crashes, especially angle and turning collisions. iRAP Toolkit notes feasibility in constrained spaces and importance of signage and speed control. Evidence on cyclist and pedestrian impacts is mixed and context-dependent.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Feasible in constrained spaces; effective at ≤50 km/h; limited reconstruction needed.	Likely feasible on urban local streets with low-moderate volumes.	May not be feasible on roads with cycle lanes or separate cycle paths or tracks
Compatibility	Aligns with standard intersection-control strategies.	Works well within broader traffic-calming programs.	Integration with high-cycling corridors or public transport routes (especially for buses)
Public Acceptance	Generally acceptable where roundabouts are familiar; acceptance improves post-installation. Design influences how well understood they are (i.e. whether road users are confused as to whether standard roundabout yielding rules apply).	Expected support for speed reduction in neighbourhoods.	Acceptance among cyclists, motorcyclists or bus operators.
Benefit–Cost Ratio	Typically >1 where injury crashes are high; favourable returns. BCRs approaching 10	Positive Return on Investment (ROI) expected at sites with recurring angle crashes.	Lifecycle cost variation.

	reported (FHWA and SafetyCube)		
Crash & Severity Reduction	Strong evidence (30–50% crash reduction).	Lower speeds and conflict-angle removal.	Effects on VRUs vary by design.
Cost-Effectiveness	Good performance relative to crash reduction.	Most effective when replacing stop-controlled intersections.	Long-term maintenance costs.
Effects on Other Road Users	Reduces speed and severity of crashes.	Reduced risk at low-volume street intersections.	Effects on bicycles, motorcyclists (safety and accommodating design) and buses (access and maneuverability).
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Widely applied worldwide and most constraints are dealt with in the literature	
Compatibility	●●○ Medium	In environments with many cyclists care needs to be exercised	
Public Acceptance	●●○ Medium	Some resistance may be initially expected since people perceive the working of a mini roundabout as different to a normal roundabout	
Benefit–Cost Ratio	●●○ Medium	Well documented	
Crash & Severity Reduction	●●● Strong	Well documented	
Cost-Effectiveness	●●○ Medium	Well documented	
Effects on Other Road Users	●○○ Weak	Effect on cyclists needs careful consideration	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>Likely impactful at intersections with vehicle conflict patterns and speed issues; suitable for constrained urban environments.</i>			
Evidence Gaps & Learning Opportunities			
<ul style="list-style-type: none"> • Limited VRU evidence • Need for maintenance cost data • Behavioural adaptation not well documented 			
Overall Assessment			
<i>A mature intervention with strong evidence for crash reduction. VRU impacts require attention, presenting learning opportunities for CAMBER.</i>			

#2: RAISED INTERSECTION

A raised intersection elevates the entire junction area to the level of adjoining sidewalks, improving visibility, lowering vehicle speeds and improving safety for pedestrians and cyclists. It reduces vehicle speeds, enhances safety for vulnerable road users, and improves accessibility in urban and residential areas.

Summary of Evidence Base

- The iRAP Road Safety Toolkit treats raised pedestrian crossings as an effective traffic calming measure at intersections, designed to slow approaching vehicles and to bring the crossing up to footway level for pedestrians, with an indicative crash reduction in the range of twenty-five to forty percent for pedestrian crashes.
- SafetyCube DDS synopsis on installation of speed humps covers trapezoidal humps, (raised pedestrian crossings) and speed humps at junctions. It reports consistent reductions in fatal and injury crashes after installation of these vertical deflection measures, confirming that raising the vehicle path at conflict points can reduce crash frequency and severity.
- International design guides that build on iRAP and the Handbook of Road Safety Measures (Elvik et.al, 2009) evidence present raised intersections and raised platforms at crossings as part of a family of vertical traffic calming treatments that reduce approach speeds, increase pedestrian visibility and emphasise pedestrian priority, especially at lower speed urban intersections.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Are widely implemented and require no major reconstruction in urban low speed areas.	Likely feasible in all pilots	Steep grades, major bus routes, or where utilities and drainage are complex.
Compatibility	Compatible with Safe System principles and with iRAP/SafetyCube emphasis on speed control at intersections.	Expected to integrate well with pedestrian zones, school areas and digital asset inventories.	Limited evidence on impacts for buses, motorcycles or automated vehicles.
Public Acceptance	Vertical calming is commonly used and generally accepted in residential areas.	Likely acceptable where slower speeds and pedestrian priority are desired.	Acceptance for heavier traffic, emergency services or motorcycles is not documented.
Benefit–Cost Ratio	Not known.	Positive BCR expected at high speed and high VRU activity intersections.	Costs increase with complex utilities; no specific BCR for raised intersections.
Crash & Severity Reduction	They show reductions in fatal and injury crashes. iRAP reports 25-40% pedestrian crash reduction for raised crossings.	Expected to reduce turning, approach/ pedestrian crashes via lower entry speeds.	

Cost-Effectiveness	Are considered to be cost effective compared with signalisation or geometric changes.	Expected to perform well when targeted at high risk intersections.	It varies with construction complexity and maintenance.
Effects on Other Road Users	They improve crossing visibility and accessibility for pedestrians and cyclists.	Likely to improve safety in mixed traffic and school environments.	Possible discomfort for buses, emergency vehicles, motorcyclists.
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Widely applied worldwide	
Compatibility	●●○	Supportive of safe speed principles in mixed use environments	
Public Acceptance	●○○ Weak	Limited evidence	
Benefit–Cost Ratio	●●○○●○ Medium	Reasonable well documented	
Crash & Severity Reduction	●●● Strong	Safe speeds and self-enforcing, well documented	
Cost-Effectiveness	●●○ Medium	As above	
Effects on Other Road Users	●●○ Medium	Limited negative impacts documented	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<p><i>Raised intersections are likely to perform better in:</i></p> <ul style="list-style-type: none"> • <i>urban and residential intersections with documented turning or crossing crashes, especially where pedestrians and cyclists are frequently present.</i> • <i>school and neighbourhood centres where the desired operating speed is thirty kilometres per hour or less.</i> • <i>locations where traditional measures such as signs and markings have not produced sufficient speed reduction through the conflict area.</i> 			
Evidence Gaps & Learning Opportunities			
<ul style="list-style-type: none"> • <i>Crash modification factor or benefit cost ratio specifically for raised intersections, separate from raised crossings or speed humps at junctions, needs more attention.</i> • <i>There is limited quantitative evidence on the long-term durability, maintenance cost, and performance of raised intersections in cold climates and under heavy traffic.</i> • <i>Effects on cyclists, motorcyclists, public transport operations, emergency services and noise are largely undocumented in the required sources.</i> • <i>CAMBER pilots could therefore generate high-value evidence by considering factors such as crashes at treated intersections, user experience for pedestrians, cyclists, and drivers. However, these studies need to be done over the course of a long time.</i> 			
Overall Assessment			

Raised intersections are a logical extension of well-established vertical deflection measures, such as raised crossings at junctions that are documented in the iRAP toolkit, SafetyCube, and guidance grounded in the Handbook of Road Safety Measures. The core mechanism is robust: lower approach and entry speeds lead to fewer and less severe crashes, and a platform at the footway level makes pedestrian presence more visible and crossing more accessible. Direct empirical evidence for full raised intersections is still limited compared with that for raised crossings and speed humps more generally. For CAMBER, raised intersections can therefore be considered a promising but relatively resource-intensive low-speed intersection treatment that is suggested to be applied selectively at high-risk sites.

#3: EDGE ISLANDS OR SPLITTER ISLANDS

Edge or Splitter Islands. They are usually placed at junction approaches to channel traffic and reduce approach speeds. They improve intersection visibility, guide turning movements, and enhance safety for pedestrians crossing at or near the intersection. Here, they are considered as part of the options for channelisation and/or delineation at intersections.

Summary of Evidence Base

Elvik et al. (2009) summarise 38 studies, taking the results from the most methodologically sound. Even then, most of the results are non-significant. They explain that “this reflects the problem of many studies, which is that only few junctions have been studied. If the results are interpreted as showing true effects, the results [assuming a drive on the right situation] can be summarised as follows:

“Left turn lanes reduce injury accidents. The effects of physical channelisation are greater than of marked channelisation, and the effects are greater at T-junctions than at X-junctions.

“Right turn lanes reduce injury accidents at X-junctions, but not at T-junctions. No effect has been found on property-damage-only accidents.

“Full channelisation reduces injury accidents at X-junctions, but not at T-junctions. The effects of physical channelisation are greater than that of marked channelisation.

“The effects of full channelisation are slightly larger than the effects of left turn lanes or right turn lanes only.

“Side road channelisation increases injury accidents at T-junctions and reduces injury accidents at X-junctions. Passing lanes reduce injury accidents at X-junctions and increase accidents at T-junctions.”

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Roadspace and land-take may be an issue	Implementable at large intersections with long crossing distances and separate turning lanes	Will they accommodate sweep of articulated vehicles and coaches?
Compatibility	Require necessary road space and width	Facilitate staged pedestrian crossing and provide refuge	As above
Public Acceptance	Anecdotally, not often a major issue	Potential hazard for cyclists and handicapped users	Delivery and truck drivers may experience discomfort

			and be unappreciative?
Benefit–Cost Ratio	BCR 3-7 for different situations at crossroads (Table 1.5.5 Elvik <i>et al.</i>)		Probable benefits where pedestrian activity is high
Crash & Severity Reduction	Crash reductions of up to and around 25% are common in Elvik <i>et al.</i> , with several outliers. toolkit.irap.org suggests reductions of 10-25% for this type of measure	Well-designed channelisation can reduce vehicle speeds	
Cost-Effectiveness	Good, but Elvik-reported (Elvik <i>et al.</i> , 2009) analyses based on AADT of 10000, so assuming flows are sufficient to justify.		Maintenance costs in tight urban situations
Effects on Other Road Users	Benefits for pedestrians as a refuge		See comments above on larger vehicles
Strength of Evidence			
	Strength	Notes	
Feasibility	●●○ Medium	Check road width and any other relevant factors	
Compatibility	●●○ Medium	See above	
Public Acceptance	●●○ Medium	See above	
Benefit–Cost Ratio	●○○ Weak	See comments of Elvik <i>et al.</i> (2019). Results are insignificant	
Crash & Severity Reduction	●○○ Weak	See above	
Cost-Effectiveness	●○○ Weak	See above	
Effects on Other Road Users	●●● Strong	By observation, benefit as a pedestrian refuge	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>Likely to perform well at high-volume major crossroads.</i>			
Evidence Gaps & Learning Opportunities			
<i>CAMBER pilots could assess collision pattern history at intersections with and without such features</i>			
<ul style="list-style-type: none"> • <i>What does such a comparison show?</i> 			

- How does the incidence of crashes involving side-impacts and shunts between vehicles and those involving pedestrians compare?

Overall Assessment

Edge and splitter islands are a particular type of channelisation and the efficacy of these interventions has been assessed within that wider category. It may be difficult to implement physical channelisation in the pilots (realignment of junction approaches, for example) but there may be opportunities using road markings to channel and/or segregate traffic.

#4: ROADSIDE ROAD RESTRAINT SYSTEMS

Roadside Road Restraint Systems such as guardrails or safety fences, prevent vehicles from leaving the roadway and colliding with hazardous roadside objects. They reduce the severity of run-off-road crashes and enhance overall roadside safety, particularly on curves and embankments.

Summary of Evidence Base

Guardrails along embankments strongly reduce the number of fatal and injury off-the road accidents. Guardrails do not have an equally great effect on all types of obstacles. Guardrails lead to a significant reduction in the severity of injuries sustained in motorised vehicle collisions with trees, rock faces and driving off the road in steep slopes. The reduction in the severity of injuries is, however, smaller regarding hitting signposts or ditches.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Roadside road restraint systems are widely used in many countries and are very effective	It is expected that road safety will improve when installing roadside barrier systems roads where run-off-road crashes occurs	The effects in constrained environments might be adverse
Compatibility	Are commonly compatible with common road-asset inventories used by road authorities.	Good fit on secondary roads with run-off-road crashes. Usually not installed on urban roads.	Effects on motorcyclists. Requires careful integration with cyclists/pedestrians
Public Acceptance	Generally high	Likely to be high	Motorcyclists do not approve of some types of safety barriers
Benefit–Cost Ratio	A cost–benefit analysis made for Norway (Elvik 2001) indicates that guardrails along embankments provide benefits that are	High in rural areas	

	greater than the costs for roads that have an AADT of more than about 3,000		
Crash & Severity Reduction	Strong evidence (50% run-off-road crash reduction) (Elvik et al., 2009).	Decrease in run-off-road crashes and run-off-road crash severity	The size and significance of the effect
Cost-Effectiveness	Unknown	Cost-effective for run-off-road crash risk.	Maintenance burden.
Effects on Other Road Users	May increase risk to cyclists and motorcyclists. Also pedestrians (especially in bridges)		Potential negative impacts on VRUs and constrained urban corridors must be carefully considered
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Widely applied, anchoring in poor soil needs attention	
Compatibility	●●○ Medium	Added risk of injury to motorcycle riders when striking uprights or top of barriers	
Public Acceptance	●●○ Medium	Limited evidence	
Benefit–Cost Ratio	●●○ Medium	Well documented.	
Crash & Severity Reduction	●●○ Medium	Effective for reducing injury and run off road crashes	
Cost-Effectiveness	●●○ Medium	Reasonable well documented	
Effects on Other Road Users	●●○ Medium	Not well documented - effect on safety of motorcycle riders of certain restraint systems	
Legend:	●●● Strong ●●○ Medium ●○● Weak ○○● None		
Likely Impact in CAMBER Context			
<i>These could be deployed on secondary rural roads in some of the pilots., particularly roads with a relatively high degree of bendiness or with hazardous objects within the road reserve or clear zone.</i>			
Evidence Gaps & Learning Opportunities			
<i>How cost effective is the measure? The benefits outweigh the costs (BCR) What are the maintenance requirements?</i>			
Overall Assessment			
<i>A well-tested intervention with some potential for CAMBER, especially on secondary roads with a high proportion of run-off-road crashes.</i>			

#5: IMPACT SENSOR INSTALLATION

Impact sensor installation involves placing sensors on safety barriers or critical structures to detect and report collisions in real time. This enables rapid emergency response, supports maintenance planning, and enhances post-crash safety management on road networks.

Summary of Evidence Base

According to the SafetyCube DSS, all benefits related with E-Call resulted from an expert panel's assessment of the eCall potential and cannot be objectively validated. The literature used in this assessment reveal little evidence of the use and efficacy of impact sensors but they offer potential for the pilots in that maintenance can be more effectively deployed and the structural integrity of the structures ensured.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	SafetyCube confirms the transferability of the results across different regions for E-Call	Effect is local only and requires maintenance. Maintenance costs may be high in remote areas	Cost-effectiveness
Compatibility	Fits secondary roads with safety barriers.		
Public Acceptance	Not known	Expected to be high as signs are relatively unobtrusive	Effects of vandalism Reliability Rate of false alarms
Benefit–Cost Ratio	Not known	Likely to be higher than 1 but not an extremely high ratio	Cost of construction and maintenance in pilot countries
Crash & Severity Reduction	Not known	Limited effect	The size and significance of the effect
Cost-Effectiveness	Not known	Barely cost-effective	Large-scale application Long-term maintenance costs.
Effects on Other Road Users	Not known		

Strength of Evidence

	Strength	Notes
Feasibility	●●○ Medium	Uncertainty about power supply and reliability
Compatibility	●●○ Medium	Integration and impact on integrity of restraint system
Public Acceptance	●●○ Medium	Not well known but likely to be accepted
Benefit–Cost Ratio	●○○ Weak	Not well documented

Crash & Severity Reduction	●○○ Weak	Not well documented
Cost-Effectiveness	●○○ Weak	Not well documented
Effects on Other Road Users	○○○ None	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>On secondary rural roads in the pilot areas and where impact attenuation and barrier systems are currently applied.</i>		
Evidence Gaps & Learning Opportunities		
<i>Effect of the measure on its own Potential vandalism Rate of false alarms Reliability of power supply Cost effectiveness BCR</i>		
Overall Assessment		
<i>An untested intervention with some potential for the pilots, particularly on remote secondary roads. Their value lies in post-crash detection and asset monitoring, rather than prevention of crashes For CAMBER, they offer potential as a digital-twin enhancement and post-crash management tool.</i>		

#6: WARNING SYSTEM FOR A SCHOOL ZONE / TEMPORARY MARKET / WORK ZONE

<i>Warning systems that detect VRUs near a school, work zone or (temporary) market and sends warning messages to VMS or even directly to approaching vehicles of the presence of potentially crossing VRUs.</i>			
Summary of Evidence Base			
<i>SafetyCube has no information on this specific measure/intervention. However, it reports that the relationship between Variable Message Signs (VMS) and crashes is not well researched or reported. The effects of VMS are measured on a behavioural level (mainly speed). Results found that VMS significantly reduce driving speed, which is a strong indicator of crash frequency and severity. SafetyCube concludes that VMS probably has a favourable effect on road safety when used in the right conditions and using appropriate messages.</i>			
Evidence Assessment by Criterion			
	Known	Expected	Uncertain
Feasibility		It is feasible to apply this measure at school zones and as a temporary measure at work zones and markets or high	

		pedestrian activity areas	
Compatibility		Facilitates potentially safer pedestrian crossing and reduces speed in the vicinity of these high risk areas	
Public Acceptance	Uncertain	High	Susceptibility to vandalism
Benefit–Cost Ratio	Not known	Likely to be low	
Crash & Severity Reduction	Not Known	Small positive effect on crashes	
Cost-Effectiveness	Not known	Mildly effective but effects are local	
Effects on Other Road Users	Not Known	Positive effect on driven speeds and heightened awareness	
Strength of Evidence			
	Strength	Notes	
Feasibility	●○○ Weak	Depends on type, in vehicle or roadside. Power supply and detection are vital to eliminate false warnings and therefore credibility	
Compatibility	●○○ Weak	Non-physical and not truly safe speed compliant, supportive	
Public Acceptance	●●○ Medium	Depending on validity of messages. Well accepted by VRU	
Benefit–Cost Ratio	●○○ Weak	Limited evidence	
Crash & Severity Reduction	●○○ Weak	Limited evidence	
Cost-Effectiveness	●○○ Weak	Limited evidence	
Effects on Other Road Users	●●○ Medium	VRUs may experience a false sense of security	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>The impact is likely to be limited. Only pilots that have school zones or these sorts of areas can draw benefit and again the measure as a local treatment will have limited local effect.</i>			
Evidence Gaps & Learning Opportunities			
<i>Effectiveness on speed reduction Degree of compliance to warnings Behaviour and attitude of VRU in zones Cost and effectiveness Applicability in isolated versus area wide situations</i>			

Overall Assessment

An untested and relatively untried intervention with potential for CAMBER, particularly where there is potential to have warning messages relayed to approaching drivers via in-car systems. If we assume similar effects of these warning systems as for VMS and slow down signs, the results could be promising (Hussain et al., 2023).

#7: WARNING SYSTEMS FOR AN UNSIGNALISED CROSSING

A behavioural-support intervention where a driver approaching an unsignalised pedestrian crossing receives an audio and/or visual warning on their smartphone. The alert is typically triggered by location-based geofencing or infrastructure-to-phone communication. The goal is to increase driver awareness, reduce missed-crossing events, and improve yielding behaviour.

Summary of Evidence Base

- *The sources do not describe smartphone-based warnings, but they consistently show that earlier detection of hazards, increased conspicuity, and enhanced driver expectancy reduce crash risk at pedestrian conflict points.*
- *SafetyCube identifies advanced warning systems and driver information systems as measures that improve attention and reduce errors where pedestrian presence is often overlooked.*
- *FHWA and iRAP emphasize that timely warning and driver guidance are essential at unsignalised crossings.*
- *Limitations relate to driver distraction, alert fatigue, limited penetration rates, inconsistent compliance, and uncertainties in real-world behaviour.*

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Require no physical modification of road infrastructure. SafetyCube/ FHWA both classify digital warning systems as highly deployable.	Expected to be feasible if the pilot site supports app uptake, and stable connectivity. No geometric constraints apply.	Feasibility uncertain where phone usage regulations, data protection rules, connectivity gaps, or low driver adoption occur.
Compatibility	SafetyCube shows that such systems can complement infrastructure measures. FHWA/iRAP: driver awareness can reinforce signs/markings.	Expected to integrate well with CAMBER digital-twin data flows and event-triggered messaging systems.	different signals for different hazards might be required.
Public Acceptance	Handbook of Road Safety /SafetyCube show mixed acceptance for in-vehicle alerts and behaviour-influencing technology; acceptance depends on trust.	Expected acceptance if warnings are infrequent, accurate, and clearly tied to safety-critical unsignalised crossings.	Acceptance among older drivers, professional drivers, is not studied. Distrust of phone-based warnings remains possible.

Benefit–Cost Ratio	Infrastructure savings are high because no physical construction is required. SafetyCube notes that digital warnings have a low marginal cost once.	Expected favourable BCR if warnings reduce late reactions at high-risk crossings or support vulnerable road users.	Unknown BCR because crash modification factors for cellphone-based warnings do not exist in the sources.
Crash & Severity Reduction	Handbook of road safety mentions that earlier hazard recognition reduces collision likelihood. FHWA shows that enhanced advance warnings at crossings improve driver yielding.	Expected reduction in pedestrian-related crashes where low visibility or poor driver expectancy leads to missed detection of unsignalised crossings.	
Cost-Effectiveness	SafetyCube classifies behavioural/feedback systems as low-cost measures when scaled digitally.	Expected high cost-effectiveness if the app is already deployed or if digital mapping is available.	Cost depends on app development, communication protocols, and driver participation.
Effects on Other Road Users	SafetyCube/ FHWA note that earlier driver awareness benefits pedestrians by reducing late braking and unsafe approach speeds.	Expected benefit for pedestrians and cyclists at unsignalised crossings, especially where no physical calming exists.	Risk of distraction from phone alerts
Strength of Evidence			
	Strength	Notes	
Feasibility	●●○ Medium	Dependant on detection possibilities and coverage and usage of drivers with smartphone technology in vehicles	
Compatibility	●○○ Weak	Little evidence	
Public Acceptance	●○○ Weak	Not well documented in sources	
Benefit–Cost Ratio	●○○ Weak	Not well documented in sources	
Crash & Severity Reduction	●○○ Weak	Not well documented in sources	
Cost-Effectiveness	●○○ Weak	Not well documented in sources	
Effects on Other Road Users	●○○ Weak	Not well documented in sources	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			

Most beneficial on secondary or peri-urban roads with unsignalised pedestrian activity, limited sight distance, or low driver expectancy. Particularly relevant where infrastructure upgrades are difficult or expensive. Likely to improve driver yielding and early deceleration if system uptake is sufficient.

Evidence Gaps & Learning Opportunities

- *Limited data on distraction risks, behavioural adaptation, and user acceptance across demographic groups.*
- *Long-term compliance needs more attention.*
- *CAMBER pilots might be able to measure: real-time yielding rates and speed profiles near unsignalised crossings.*
- *Is it limited to smartphone or could it be linked to vehicle SatNav etc.?*
- *Could this be extended to other elements of CAMBER – e.g. highlighting road sections that are highlighted as high-risk on iRAP rating?*

Overall Assessment

This intervention is conceptually aligned with the mechanisms supported in the sources, namely earlier hazard detection and improved driver expectancy. However, direct empirical evidence is lacking in the sources for cellphone-based in-vehicle warnings. The safety logic is sound but unproven. CAMBER pilots, therefore, might be able to generate evidence on real-world performance, user acceptance, and operational reliability of this intervention.

#8: ADVANCE WARNING SIGNS WITH CURVE SYMBOL AND ADVISORY SPEED

Advance warning signs with curve symbol and advisory speed: Advance warning signs with a curve symbol and advisory speed inform drivers about an approaching bend and the safe speed to navigate it. This intervention enhances driver anticipation, supports appropriate speed choice, and reduces loss-of-control and run-off-road crashes, especially on rural secondary roads.

Summary of Evidence Base

According to Elvik et al. (2009), signs showing the recommended speed have been found to reduce the number of accidents by about 15–30%. However, these results are based on three studies from 1972 or earlier. Also, studies of the effects of recommended speed in curves have found small or no effects on speed.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Proven effective on rural roads and easy to implement	The effect is local only and requires maintenance. Reasonably effective on urban roads	The duration signs remain effective
Compatibility	Fully aligned with iRAP and SafetyCube hazard-recognition guidance.	Good fit with digital twin asset inventories.	Interaction with ADAS/perception systems unclear.
Public Acceptance	Familiar and generally uncontroversial; no	Expected to be high as signs are relatively	Potential over-signing or clutter concerns.

	issues noted in the sources.	unobtrusive and provided signs and advisory speeds are credible	
Benefit–Cost Ratio	The BCR are greater than one when the traffic volume is 500 vehicles per day or more. Cost–benefit ratios increase with a decreasing slope as traffic volume increases (<i>Elvik et al., 2009</i>)	Likely to be higher than 1, but not an extremely high ratio	Cost of construction and maintenance in pilot countries.
Crash & Severity Reduction	30% reduction in injury accidents in curves	Expected reductions in late braking and approach-speed errors.	Maintenance and retroreflective degradation vary.
Cost-Effectiveness	iRAP and SafetyCube classify signage as a cost-effective network treatment.	Good performance when targeted at known hazards.	Large-scale application
Effects on Other Road Users	Only motorised traffic in the vicinity of the signs	Advisory speed signs require credibility and application consistency for effectivity	Multimodal impacts are unstudied; there is a risk of clutter.
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Widely used internationally	
Compatibility	●●○ Medium	Informative and supportive intervention, not curative	
Public Acceptance	●●○ Medium	Reasonably well documented in consulted sources	
Benefit–Cost Ratio	●●○ Medium	Reasonably well documented in consulted sources	
Crash & Severity Reduction	●●○ Medium	Reasonably well documented in consulted sources	
Cost-Effectiveness	●●○ Medium	Reasonably well documented in consulted sources	
Effects on Other Road Users	●○○ Weak	Unknown, not likely to be any effects unless barrier working	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			

Advance warning signs can improve safety in pilots where the road environment is not self-explaining from a speed perception perspective, on approaches to potentially dangerous curves.

Evidence Gaps & Learning Opportunities

Further evaluation is needed to understand the long-term interaction between specific fixed warning signs and driver risk compensation behaviour, particularly how fixed signage compares to dynamic or integrated systems.

Crash modification factors are not extensively investigated for newly installed advance warning signs in the sources.

Cost effectiveness

BCR

Overall Assessment

Advance warning signs are aligned with Safe System principles and are widely supported as essential tools for hazard anticipation. While direct empirical evidence for new installation is limited, the mechanism of action and the supporting evidence from sign-placement and visibility studies indicate a clear potential for reducing crash risk at curves. Effectiveness is likely to be greater if signs are applied in a systematic way over the whole network, bringing credibility and supporting the right driver expectancy. An intervention with some potential for the pilots, particularly as a warning or advisory device in combination with other interventions.

#9: VISUAL HAZARD WARNINGS ON CURVES

Visual hazard warnings on curves (chevrons, signs): Visual hazard warnings on curves, such as chevron boards or directional arrows, guide drivers through bends by clearly indicating the curve's alignment.

A horizontal curve requires a change in vehicle path alignment and a potential reduction in vehicle speed. The change from a straight road section to a curve may present a challenging task during adverse driving conditions or for inattentive drivers.

Delineation treatments provide advance warning on the approach to a curve and positive guidance throughout the curve.

These measures enhance visibility, encourage appropriate speed reduction, and reduce run-off-road and loss-of-control crashes, especially in low-light or high-speed conditions.

Summary of Evidence Base

SafetyCube results show that installing chevron signs at curves mostly reduces crash frequency and vehicles' mean speed. The presence of chevrons also leads drivers to keep a proper lane position.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Proven effective on rural roads and easy to implement	The effect is local only and requires maintenance. Reasonably effective on urban roads	The duration signs remain effective

Compatibility	Fully aligned with iRAP and SafetyCube hazard-recognition guidance.	Good fit with digital twin asset inventories.	Interaction with ADAS/perception systems unclear.
Public Acceptance	Familiar and generally uncontroversial; no issues noted in the sources	Expected to be acceptable where the curve risk is evident.	Potential over-signing or clutter concerns.
Benefit–Cost Ratio	Best estimate of 2,7 with reduction in injury and PDO crashes of 2,6%	Likely to be higher than 1 but not an extremely high ratio	Cost of construction and maintenance in pilot countries
Crash & Severity Reduction	According to Elvik et al. (2009), chevron markings have been found to reduce accidents by 32%.	Expected reductions in late braking and approach-speed errors.	Maintenance and retroreflective degradation vary.
Cost-Effectiveness	iRAP and SafetyCube classify signage as a cost-effective network treatment.	Good performance when targeted at known hazards.	Large-scale application
Effects on Other Road Users	Only motorised traffic in the vicinity of the signs		Multimodal impacts are unstudied.
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Widely used internationally	
Compatibility	●●○ Medium	Informative and supportive intervention, not curative	
Public Acceptance	●●○ Medium	Reasonably well documented in consulted sources	
Benefit–Cost Ratio	●●○ Medium	Reasonably well documented in consulted sources	
Crash & Severity Reduction	●●○ Medium	Reasonably well documented in consulted sources	
Cost-Effectiveness	●●○ Medium	Reasonably well documented in consulted sources	
Effects on Other Road Users	●○○ Weak	Unknown, unlikely to be any effect	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>Visual hazard warnings on curves (chevrons, signs) can improve safety in pilots where the road environment is not self explaining from a speed perception perspective, on approaches to dangerous curves.</i>			

Evidence Gaps & Learning Opportunities

Cost effectiveness
BCR

Overall Assessment

Visual hazard warnings on curves are installed to quickly make an existing road more self-explaining and are aligned with Safe System principles, pending redesign. They are widely supported as essential temporary tools for hazard anticipation. An intervention with some potential for the pilots, particularly as a warning or advisory device in combination with other interventions.

#10: HIGH-CONTRAST EDGE AND CENTRELINES

High-contrast edge and centrelines: Using bright or retroreflective materials to improve lane visibility, especially at night or in wet conditions. They enhance driver guidance, reduce lane departure risks, and support safer navigation on rural and secondary roads.

Summary of Evidence Base

- According to Elvik et al. (2009), no effects on accidents have been found after the installation of different types of marked edge or centre lines.
- According to the Crash Modification Factors Clearinghouse (<https://cmfclearinghouse.fhwa.dot.gov/>), the installation of contrast pavement markings reduces run-off-the-road and sideswipe crashes by 16%.
- Toolkit.irap.org suggests 10-25% casualty reduction may be possible if context is worn or non-existent current markings
- Other sources identify improved curve delineation and pavement markings at horizontal curves as important low-cost treatments, which help drivers recognise curves earlier, choose appropriate speed, and maintain lane position.
- FHWA studies on horizontal curve warning pavement markings show fewer expected total, fatal plus injury, run off-road, nighttime and nighttime run off-road crashes where conspicuous pavement markings are applied in advance of and through curves, demonstrating that strong visual cues on the pavement can be effective.
- Dirección-General de Tráfico (DGT, 2020) has started to use special coloured markings such as red circles in dangerous curves and red lines or green lines on certain secondary roads to highlight sections with high crash risk or overtaking prohibitions, confirming that surface colour is being introduced in practice for high-risk curves, although quantitative effects are not yet published.

None of the sources provides crash modification factors specifically for high-contrast edge and centrelines

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	They are deployed without geometric changes. Installation is possible within routine maintenance, by standard paints/thermoplastics.	Likely feasible on secondary roads during marking or resurfacing.	Durability under winter maintenance and aesthetic restrictions is not documented.

Compatibility	Are commonly compatible with common road-asset inventories and signing strategies used by road authorities.	Expected to integrate with CAMBER's digital-twin and data-management layers because the markings are discrete, easily codified elements.	Uncertain when applied in environments with advisory cycle lanes, bus priority, or high visual complexity.
Public Acceptance	Not known	Expected to be acceptable on rural and secondary roads.	
Benefit–Cost Ratio	Not known	Likely to be higher than 1 but not an extremely high ratio	Cost of construction and maintenance in pilot countries
Crash & Severity Reduction	Installation of contrast pavement markings reduces run-off-the-road and sideswipe crashes by 16%	Dependent on the quality of initial markings.	
Cost-Effectiveness		May be cost-effective on the highest-risk curves when used selectively.	Lifecycle cost/ incremental safety gain not documented.
Effects on Other Road Users			
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Extensively used worldwide, applicable to most road environments and limited constraints	
Compatibility	●●● Strong	Supportive of safe system concepts, self explaining roads	
Public Acceptance	●●○ Medium	Attention to skid resistance for motorcycles/2-wheelers.	
Benefit–Cost Ratio	●●○ Medium	Reasonably well documented in consulted sources	
Crash & Severity Reduction	●○○ Weak	Reported effects are marginal	
Cost-Effectiveness	●●○ Medium	Reasonably well documented in consulted sources	
Effects on Other Road Users	●○○ Weak	Not well documented	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>On secondary roads of pilots.</i>			
Evidence Gaps & Learning Opportunities			
<i>Effect of the measure on its own</i>			

Cost effectiveness BCR
Overall Assessment
An unresearched intervention with some potential for the pilots, particularly on secondary roads.

#11: SUPERELEVATION MODIFICATION

Superelevation modification: Superelevation modification adjusts the road's cross slope on curves to counteract lateral forces acting on vehicles. This geometric improvement enhances stability, reduces skidding or rollover risks, and improves safety and comfort when navigating curves at appropriate speeds.

Summary of Evidence Base

According to Elvik et al. (2009), most of these studies have investigated improvements in superelevation based on design standards or curve speed models, rather than the effects of increased or reduced superelevation. Reduced accident rates in curves with improved superelevation were observed in some cases. It is unclear the precise extent to which results from studies will transfer to roads in the CAMBER study, but likely that benefits would be achieved by tackling this issue at high-risk locations.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Generally feasible in secondary roads.	Overall, superelevation is not applied in urban roads	
Compatibility	Works well in secondary roads.		
Public Acceptance	Not an issue		
Benefit–Cost Ratio	Not known	Likely to be higher than 1 but not an extremely high ratio. Costs likely to be relatively high compared with other "low-cost measures".	Cost of construction and maintenance in pilot countries
Crash & Severity Reduction	Reduced accident rates in curves with improved superelevation were found by different studies (Elvik et al., 2009)		
Cost-Effectiveness	Not known		
Effects on Other Road Users			

Strength of Evidence		
	Strength	Notes
Feasibility	●●○ Medium	Existing roads require major reconstruction so not easy to implement unless part of reconstruction or new projects
Compatibility	●●○ Medium	Supportive of self explaining road design but may compromise safe speed
Public Acceptance	●●○ Medium	Standard measure so acceptance is high provided degree of superelevation is within limits for heavy goods vehicles
Benefit–Cost Ratio	●●○ Medium	Reasonably well documented in consulted sources
Crash & Severity Reduction	●●○ Medium	Reasonably well documented in consulted sources
Cost-Effectiveness	●○○ Weak	Relatively expensive as a stand alone intervention, more effective as an integrated project solution
Effects on Other Road Users	○○○ None	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>On secondary roads of pilots.</i>		
Evidence Gaps & Learning Opportunities		
<i>Effect of the measure on its own</i> <i>Cost effectiveness</i> <i>BCR</i>		
Overall Assessment		
<i>A well-tested intervention with some potential for CAMBER on secondary roads.</i>		

#12: SURFACE COLOURING AT SHARP HORIZONTAL CURVES

Using contrasting pavement colours to highlight the bend and alert drivers to reduce speed. This visual cue improves curve recognition, enhances driver attention in low-visibility conditions, and helps prevent lane departures and run-off-road crashes.

Summary of Evidence Base

- *Application of high grip pavement surface treatments, combined with red colouring.*
- *FHWA studies on horizontal curve warning pavement markings show fewer expected total, fatal plus injury, run-off-road, nighttime and nighttime run-off-road crashes where conspicuous pavement markings are applied in advance of and through curves, demonstrating that strong visual cues on the pavement can be effective.*
- *Dirección-General de Tráfico has started to use special coloured markings such as red circles in dangerous curves and red lines or green lines on certain secondary roads to*

highlight sections with high crash risk or overtaking prohibitions, confirming that surface color is being introduced in practice for high-risk curves, although quantitative effects are not yet published.

None of the sources provides crash modification factors specifically for coloured surfacing at curves.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Curve markings and delineation upgrades are routinely implemented with standard materials (iRAP, FHWA).	Likely feasible on secondary roads during marking or resurfacing.	Durability under winter maintenance and aesthetic restrictions not documented.
Compatibility	Enhanced curve delineation aligns with iRAP and SafetyCube recommendations.	Expected compatible with CAMBER digital inventories and route-treatment logic.	Interaction with bicycle lanes and ADAS detection is undocumented.
Public Acceptance	High-visibility curve markings are standard and generally accepted; public communications show positive framing.	Expected acceptable where curve risk is evident.	No studies on user acceptance of coloured surfacing
Benefit–Cost Ratio	Curve delineation is low-cost and rated cost-effective (FHWA, iRAP).	Positive BCR expected in curves have documented run-off-road crashes.	No BCR studies for coloured surfaces; material and renewal costs are uncertain.
Crash & Severity Reduction	FHWA reports fewer run-off-road and nighttime crashes with enhanced pavement curve markings.	Surface colour likely to increase conspicuity and reduce entry speeds at sharper curves.	No CMFs for coloured surfacing; long-term effect and driver habituation unclear.
Cost-Effectiveness		May be cost-effective on the highest-risk curves when used selectively.	Lifecycle cost/ incremental safety gain not documented.
Effects on Other Road Users	Better curve visibility generally benefits driver safety.	Expected beneficial for VRUs if friction remains adequate.	No evidence on friction or wet-condition visibility.

Strength of Evidence

	Strength	Notes
Feasibility	●●○ Medium	Reasonably well documented in consulted sources
Compatibility	●○○ Weak	Not well documented
Public Acceptance	●○○ Weak	Not well documented

Benefit–Cost Ratio	●○○ Weak	Not well documented
Crash & Severity Reduction	●●○ Medium	Not well documented
Cost-Effectiveness	●○○ Weak	Not well documented
Effects on Other Road Users	●○○ Weak	Not well documented
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<p><i>Surface colouring is likely to perform best where:</i></p> <ul style="list-style-type: none"> • <i>run-off-road and head-on crashes are dominant crash types,</i> • <i>existing signing and standard markings have not produced sufficient speed reduction, and</i> • <i>there is a need for route treatments that do not involve major reconstruction.</i> <p><i>It is particularly relevant where visibility is reduced by alignment, vegetation, or weather, and where strong visual cues at the pavement level can reinforce curve warning signs.</i></p>		
Evidence Gaps & Learning Opportunities		
<ul style="list-style-type: none"> • <i>The sources do not focus on providing crash-based evaluations or cost data specifically for coloured surfacing at curves.</i> • <i>The incremental effect of colour compared with strong conventional markings and chevrons needs more investigation.</i> • <i>Durability, friction performance, and maintenance needs for coloured materials under European environmental and traffic conditions are not documented.</i> <p><i>Within CAMBER pilots, this intervention might offer an opportunity to measure:</i></p> <ul style="list-style-type: none"> • <i>changes in speed profiles at treated curves,</i> • <i>driver eye glance patterns or self-reported awareness where feasible,</i> • <i>incident and crash trends over time.</i> 		
Overall Assessment		
<p><i>Surface colouring at sharp horizontal curves is consistent with the mechanisms and principles emphasised by iRAP, SafetyCube and FHWA for curve safety. The general effectiveness of improved pavement markings and curve delineation is supported by empirical studies, but coloured surfacing itself has not yet been evaluated in these sources. CAMBER might therefore consider this intervention as an extension of established curve marking treatments.</i></p>		

#13: IMPROVED SIGN PLACEMENT AND NIGHTTIME VISIBILITY

This intervention consists of improving the placement, conspicuity and retroreflective quality of signs and pavement markings to enhance guidance and hazard recognition in darkness and low visibility on rural and secondary roads.

Summary of Evidence Base

- Studies consistently report that improved sign placement, retroreflective sheeting and high quality pavement markings reduce nighttime crashes, particularly run-off-road and intersection crashes.
- Regarding markings, there are conflicting results on the effect on crash risk of high retroreflective markings (above 100 mcd/m²/lx. (e.g. Hauer, E. (2019). On the relationship between road safety research and the practice of road design and operation. Accident Analysis & Prevention, V.128, pp 114-131. <https://doi.org/10.1016/j.aap.2019.03.016>
- The main mechanisms are earlier detection of hazards, clearer preview of alignment and conflict points, and reduced missed or late responses to warning signs.
- Limitations include dependence on maintenance of retroreflectivity, the risk of visual clutter where many devices are added, and limited long term evaluations in complex multimodal environments.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	iRAP classifies delineation improvements as implementable on most road types.	Feasible with existing signing infrastructure. Upgrades can be integrated into routine inspections, nighttime audits, or retroreflective replacement cycles. Service life of high retroreflective material is higher than for lower grade material.	Constraints in visually complex junctions where additional signing risks clutter. Durability in harsh climates remains less documented.
Compatibility	iRAP and SafetyCube classify sign visibility as a core infrastructure safety element.	High compatibility is expected since signs are discrete assets with measurable performance attributes.	Interaction with ADAS is not yet fully evaluated.
Public Acceptance	Are highly familiar and rarely controversial. Handbook of road safety notes no public-acceptance issues linked to correcting substandard signs.	Acceptance likely high in pilot areas where nighttime visibility problems are known and upgrades do not introduce discomfort or restrictions.	Limited evidence on acceptance among older drivers sensitive to glare, or residents concerned about visual intrusion.
Benefit–Cost Ratio	Cost data show sign upgrades are low-cost with favourable returns, especially where nighttime crash burden is high.	For sites with identifiable nighttime risks, BCR is expected to exceed one due to low material/labour cost and long service life.	Exact BCR for each pilot site remains uncertain until site-specific crash-by-light-condition, unit costs.
Crash & Severity Reduction	Elvik et al. (2009) report 15% reduction in injury crashes and 7% reduction in crashes after correcting sign placement.	Expected crash reduction on CAMBER roads at curves, unsignalised intersections, and pedestrian-conflict	Limited before-and-after studies; uncertain effect magnitude in already well-signaled

	SafetyCube and FHWA confirm improved conspicuity reduces run-off-road.	locations where poor visibility or late detection is documented.	environments or where multiple competing visual stimuli are present.
Cost-Effectiveness	Elvik et al. (2009) report a low cost (NOK 1.5-3 K per sign replacement). SafetyCube: sign/delineation improvements are cost-effective.	Expected high cost-effectiveness for CAMBER pilots due to modest cost and broad applicability on rural/secondary networks.	Dependent on long-term retroreflectivity maintenance and environmental wear remain insufficiently quantified.
Effects on Other Road Users	Improved guidance aids pedestrians and cyclists. iRAP notes improved delineation particularly benefits vulnerable users.	Positive effects where nighttime visibility is poor, especially at pedestrian crossings, bus stops, or mixed-traffic segments.	Glare, increased visual load, or masking of informal pedestrian paths are not well quantified.
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Widely applied, researched and documented	
Compatibility	●●○ Medium	Supportive of safe systems, requirements pilot specific	
Public Acceptance	●○○ Weak	Not well known, only very old research relating to public acceptance	
Benefit–Cost Ratio	●●○ Medium	Low-cost measure with small safety impact	
Crash & Severity Reduction	●●● Strong	Well documented	
Cost-Effectiveness	●●○ Medium	Well documented	
Effects on Other Road Users	●○○ Weak	Aimes at specific road user groups, site specific	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>Most effective on rural and secondary roads with known nighttime crashes, inconsistent sign visibility, or poor delineation. Particularly valuable at curves, unsignalised intersections, school-area crossings, and dark approach sections where drivers rely heavily on signing and retroreflective cues for preview time and hazard anticipation.</i>			
Evidence Gaps & Learning Opportunities			
<ul style="list-style-type: none"> Limited data on retroreflective performance decay in winter climates and differences across sign materials. Lack of research on glare and cognitive load for older drivers. 			

- Opportunity for CAMBER pilots that they might be able to measure: nighttime speed profiles, detection distances, driver workload, and user acceptance before and after implementation.

Overall Assessment

Improved sign placement and nighttime visibility are mature, low-cost, and operationally straightforward measures supported by consistent guidance across all sources. Evidence suggests a significant potential for reducing crashes, particularly nighttime run-off-road and intersection crashes. Although the safety mechanism is well understood, empirical evidence remains limited, with studies being the primary source of information.

#14: ADVANCE WARNING SIGNS FOR CURVES, INTERSECTIONS, OR SCHOOLS

Advance warning signs are inexpensive traffic control measures used to alert drivers to upcoming hazards that require speed reduction or a change in manoeuvre (e.g. sharp curves, complex intersections, or pedestrian zones like schools)

Summary of Evidence Base

- All sources recognise advance warning signs as essential components of safe infrastructure, especially where geometry, visibility, or unexpected hazards increase driver workload. They function by increasing preview time and reducing missed warnings, two critical factors that contribute to crashes.
- The Handbook of Road Safety Measures provides evidence that legally compliant and correctly placed signs significantly improve hazard recognition. While the Handbook's strongest numerical evidence relates to correcting sign-placement errors (15% injury crash reduction), this mechanism applies directly to advance warning signs: correct placement + improved visibility = better driver preparedness.
- Although none of the sources provide crash modification factors specifically for "advance warning signs," all confirm that early information and good conspicuity reduce late reactions, inappropriate speeds, and conflict-likelihood at curves, intersections, and school zones.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Advance warning signs is low-cost, and can be done without geometric changes.	Expected to integrate into standard resurfacing and marking cycles.	Feasibility may be limited in visually saturated environments. Visibility challenges due to vegetation
Compatibility	Fully aligned with iRAP and SafetyCube hazard-recognition guidance.	Good fit with digital twin asset inventories.	Interaction with ADAS/perception systems unclear.
Public Acceptance	Familiar and generally uncontroversial; no issues noted in the sources.	Likely accepted where hazards are frequent.	Potential over-signing or clutter concerns.
Benefit–Cost Ratio	Low installation cost; Handbook of road safety	Likely >1 at high-risk curves,	Lack of sign-specific BCR studies.

	supports low-cost sign upgrades.	intersections, schools.	
Crash & Severity Reduction	Elvik shows that sign correction reduces injury crashes by 15 percent, PDO crashes by 7 percent.	Expected reductions in late braking and approach-speed errors.	No CMF for newly installed signs.
Cost-Effectiveness	iRAP and SafetyCube classify signage as cost-effective network treatment.	Good performance when targeted at known hazards.	Maintenance and retroreflective degradation vary.
Effects on Other Road Users	Better driver awareness benefits VRUs near curves/intersections/schools.	Positive where pedestrians or cyclists are present.	Multimodal impacts unstudied; risk of clutter.
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Widely used internationally	
Compatibility	●●○ Medium	Informative and supportive intervention, not curative	
Public Acceptance	●●○ Medium	Reasonably well documented in consulted sources	
Benefit–Cost Ratio	●●○ Medium	Reasonably well documented in consulted sources	
Crash & Severity Reduction	●●○ Medium	Reasonably well documented in consulted sources	
Cost-Effectiveness	●●○ Medium	Reasonably well documented in consulted sources	
Effects on Other Road Users	●○○ Weak	Unknown, unlikely to be any effect	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>This intervention is likely to perform best in locations where:</i>			
<ul style="list-style-type: none"> • sharp curves have high run-off-road or lane-departure crashes, • unsignalised intersections have limited sight distance or surprise conflict points, • school zones require consistent speed reduction and driver readiness, • nighttime or low-visibility conditions degrade natural driver preview. 			
Evidence Gaps & Learning Opportunities			
<ul style="list-style-type: none"> • Further evaluation is needed to understand the long-term interaction between specific fixed warning signs and driver risk compensation behaviour, particularly how fixed signage compares to dynamic or integrated systems. • Crash modification factors are not extensively investigated for newly installed advance warning signs in the sources. • Limited understanding of the interaction between sign visibility, driver workload, and multimodal complexity. 			

- No explicit evidence on nighttime vs. daytime performance differences outside general sign-placement studies.
- CAMBER may be used to evaluate:
 - speed reduction at different warning distances,
 - compliance and attention patterns,
 - conflicts involving VRUs at school zones and intersections.

Overall Assessment

Advance warning signs are aligned with Safe System principles and are widely supported as essential tools for hazard anticipation. While direct empirical evidence for new installation is limited, the mechanism of action and the supporting evidence from sign-placement and visibility studies indicate a clear potential for reducing crash risk at curves, intersections, and school zones. There may sometimes be an over-reliance on the effect of such signing and that public expectations of their effect can be too high.

#15: ALTERNATING ROAD MARKINGS

Creating visual stimuli (e.g. Dragon Teeth, Coloured Markings/Lanes) that signal upcoming transitions, like speed reductions or pedestrian areas. They attract driver attention, enhance speed awareness, and improve compliance with local traffic regulations, particularly at gateways or curve approaches.

Summary of Evidence Base

- Visual-stimulus markings reduce approach speeds by approximately 3-10 km/h in curves, school approaches, and pedestrian conflict zones.
- They work through visual salience and expectancy mechanisms, prompting earlier and more consistent speed adaptation.
- Limitations include variability in durability across climates, mixed findings in dense multimodal environments, and limited long-term crash-based evaluations.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	They are deployed without geometric changes. Installation is possible within routine maintenance, by standard paints/thermoplastics. W/O structural modification.	Expected to integrate into existing work programmes and traffic-management procedures with minimal operational disruption.	Poor pavement condition, steep gradients, or complex multimodal layouts where visibility and durability may degrade. Long-term maintenance requirements.
Compatibility	Are commonly compatible with common road-asset inventories and signing strategies used by road authorities.	Expected to integrate with CAMBER's digital-twin and data-management layers because the markings are discrete, easily codified elements.	Uncertain when applied in environments with advisory cycle lanes, bus priority, or high visual complexity.
Public Acceptance	The literature shows generally positive		While coloured markings are widely

	acceptance. Non-intrusive visual measures are preferred to vertical deflections and are rarely opposed.		recommended, confusion can arise from complex patterns. Noise issues in residential areas.
Benefit–Cost Ratio	SafetyCube analyses classify perceptual markings as low-cost measures with positive safety impacts. Existing evidence shows high economic viability.	BCR is expected to exceed one with identifiable crash risks, given low installation costs, reductions in approach speeds, and conflict probability.	Precise BCR values remain uncertain until site-specific crash histories, unit costs, and time horizons are applied.
Crash & Severity Reduction	Reductions of approximately 3 km/h in mean speed on curves, school approaches, and pedestrian-conflict zones. SafetyCube classifies consistent positive effects on crash likelihood.	Expected to reduce run-off-road crashes, loss-of-control events on curves, and pedestrian conflicts at crossings,	Long-term crash modification factors are uncertain due to limited before-and-after studies.
Cost-Effectiveness	SafetyCube and European low-cost safety guidance confirm high cost-effectiveness compared to structural or geometric modifications. Material/labour costs are low/	Expected to rank highly on cost-effectiveness because many locations can be treated with modest budgets while achieving quantifiable safety benefits.	Uncertain where coloured surfacing deteriorates quickly under winter maintenance or high traffic, leading to higher-than-expected renewal costs.
Effects on Other Road Users	Evidence shows improved conspicuity and reduced approach speeds that benefit pedestrians and cyclists at crossings and conflict points.	Expected to improve safety for vulnerable users at curves and crossing approaches.	Potential unintended effects, such as visual overload for older drivers, misinterpretation by cyclists, or displacement of risk to adjacent links. Road surface friction compromised may be an issue for braking motorcyclists.
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Widely used internationally	
Compatibility	●●● Strong	Informative and supportive intervention, not curative	
Public Acceptance	●●○ Medium	Reasonably well documented in consulted sources	

Benefit–Cost Ratio	●●○ Medium	Reasonably well documented in consulted sources
Crash & Severity Reduction	●●○ Medium	Reasonably well documented in consulted sources
Cost-Effectiveness	●●○ Medium	Reasonably well documented in consulted sources
Effects on Other Road Users	●●○ Medium	Unknown
Legend:	●●● Strong ●●○ Medium ●○● Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>The intervention is likely to perform well on secondary and urban roads with moderate speeds, clearly defined conflict points, and identifiable speed-compliance problems. It is particularly suitable for curve approaches, school areas, pedestrian crossing approaches, and sections where visibility and driver expectancy require reinforcement.</i>		
Evidence Gaps & Learning Opportunities		
<ul style="list-style-type: none"> • <i>Limited long-term crash-based evaluations outside of gateway contexts.</i> • <i>Uncertainty regarding impacts in complex multimodal environments with cyclists and buses.</i> • <i>Limited evidence on the durability and performance under winter maintenance.</i> • <i>CAMBER pilots might be able to quantify speed reductions, user acceptance, and durability under varying conditions.</i> • <i>Is effectiveness time-limited? Do local drivers become too familiar with the measures and realise that the measures will not necessarily require a lower speed?</i> 		
Overall Assessment		
<i>Visual-stimulus road markings offer a low-cost, low-disruption intervention with consistent evidence of speed reduction and improved conspicuity in transition zones. They align well with EU design practice and CAMBER’s emphasis on scalable, low-cost safety measures. However, multimodal impacts and long-term durability require further study. Overall, the intervention is promising but benefits from structured monitoring in pilot deployments.</i>		

#16: DYNAMIC SPEED FEEDBACK SIGNS

Dynamic speed feedback signs: Dynamic speed display signs (DSDSs) measure the speed of approaching vehicles and communicate the speed to drivers on a digital display along the road. The underlying idea is that DSDSs help motorists self-enforce their speed. There are also mandatory dynamic variable speed limit signs which give maximum speed limits depending on, for example, weather or prevailing traffic conditions.

Summary of Evidence Base

SafetyCube (<https://www.roadsafety-dss.eu/#/>) results show that dynamic speed display signs (DSDSs) have favourable effects on speeds. One study also shows a decrease of the number of crashes after installing DSDSs.

The available literature shows that dynamic speed limits (DSLs) have favourable effects on driving speeds and on the number of crashes. However, the number of empirical results is very limited and results should be confirmed by additional research.

Evidence Assessment by Criterion			
	Known	Expected	Uncertain
Feasibility	Proven effective on rural roads and relatively easy to implement	Effect is local only and requires maintenance. Reasonably effective on urban roads	The duration signs remain effective Cost-effectiveness
Compatibility		Speed limits signs require enforcement so effectivity dependent on camera's or other	
Public Acceptance		Expected to be high as signs are relatively unobtrusive	Effects of vandalism Reliability
Benefit–Cost Ratio	0,7-1,1, so not very effective in rural areas	Maintenance costs high in remote areas	In urban areas
Crash & Severity Reduction	0.95 (dynamic speed feedback sign on curves in rural roads), in the CMF Clearinghouse $\frac{4}{5}$ stars quality rating. ¹⁵ 0.49~0.69 injury accidents (variable speed limit), in CMF Clearinghouse $\frac{3}{5}$ & $\frac{4}{5}$ stars quality ratings. ¹⁵	Limited effect	
Cost-Effectiveness	Marginally effective	Barely cost-effective	Large scale application
Effects on Other Road Users	Only motorized traffic in the vicinity of signs	Speed limits signs require enforcement so effectivity	
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Dependent on power supply (or feasibility of solar panels).	
Compatibility	●●● Strong	Safe systems ask for essentially self explaining design. When conditions warrant other behaviour, these signs support warning of changing risk	

¹⁵ <https://cmfclearinghouse.fhwa.dot.gov/results.php>

Public Acceptance	●●○ Medium	Susceptible to vandalism
Benefit–Cost Ratio	●●○ Medium	Rural roads studied, little evidence urban
Crash & Severity Reduction	●●○ Medium	The effect on crashes is small, although the measure is effective
Cost-Effectiveness	●●○ Medium	
Effects on Other Road Users	●●○ Medium	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>In pilots where the road environment is not self explaining from a speed perception perspective and where weather or environmental conditions warrant lower limits.</i>		
Evidence Gaps & Learning Opportunities		
<i>Potential vandalism Reliability of power supply Cost effectiveness BCR</i>		
Overall Assessment		
<i>An intervention with limited evidence in the consulted sources, but with some potential for the pilots, particularly as a warning or advisory device in combination with other interventions.</i>		

#17: SPEED HUMPS / CUSHIONS / TABLES

<i>Speed humps as a general term for any vertical speed deflection devices that aim to reduce the speeds of motor vehicle traffic, particularly in urban and residential areas. It includes: road-wide measures such as speed humps, speed bumps (narrower and steeper than humps) and speed tables (flatter and wider than humps); along with speed cushions (allow larger vehicles and cyclists to pass in between the cushions), and also raised crossings, which have a dual function of slowing down traffic and allowing pedestrians a safer place to cross.</i>			
Summary of Evidence Base			
<i>Studies on the safety effects of speed hump installation show that accident rates and vehicle speeds are reduced when installed. The SafetyCube DSS reports that in half of the analysed studies, the results were significantly positive (reduction in speeds and crashes). In the other half of the studies, no statistical analysis was undertaken, so it is not known whether these results were significant. However, what is clear is that none of the results showed that speed humps resulted in increased speeds or accident rates. Hence, it can be concluded that installing speed humps reduces road safety risk.</i>			
Evidence Assessment by Criterion			
	Known	Expected	Uncertain

Feasibility	Speed humps and other vertical devices aimed at speed reduction are best applied on low speed roads with long straight sections and mixed road use, or at intersections between lower order roads (collector/access)	The use of speed humps and similar devices is expected to cause some vibration in the surrounding area. The effects of the measure (on speed and crashes) are localized. Not suited for high speed roads.	Effectiveness of other forms of vertical devices, ie bus friendly humps
Compatibility	The use of speed humps and similar devices support safe system goals in minimizing speed differences between vulnerable and high speed road users	Facilitates improved pedestrian crossing. In combination with intersections, helps distinguish between road types and improve priority assignments	Impact on drainage, maintenance and pavement skid resistance
Public Acceptance	Generally high among residents, resistance from Public Transport (PT)and emergency service operators	Some resistance from regular users	
Benefit–Cost Ratio	High (18,2:1) for speed humps, benefits way exceeds costs	Expected to be similar or lower for other forms of vertical speed control devices	Uncertain for speed devices designed specifically for one type of motorized traffic (i.e. bus)
Crash & Severity Reduction	17% reduction injury crashes according to SafetyCube DSS 0.07~0.44 (install speed humps in rural roads), in the CMF Clearinghouse ⁴ / ₅ stars quality rating (0.21~0.87 in ³ / ₅ star quality rating) ¹⁶		Effectiveness of other forms of vertical devices, i.e. bus friendly humps
Cost-Effectiveness	An extremely cost-effective measure		

¹⁶ <https://cmfclearinghouse.fhwa.dot.gov/results.php>

Effects on Other Road Users	Effects limited to motorized traffic	
Strength of Evidence		
	Strength	Notes
Feasibility	●●○ Medium	Subject to planning and other procedures in pilot countries
Compatibility	●●○ Medium	
Public Acceptance	●●○ Medium	Attention for PT, EMS and HGV traffic
Benefit–Cost Ratio	●●● Strong	
Crash & Severity Reduction	●●● Strong	
Cost-Effectiveness	●●● Strong	
Effects on Other Road Users	●○○ Weak	Effects are aimed at motorised traffic only and there is likely resistance to be expected from PT, EMS and HGV operators
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>Positive short term impact on speed on roads and intersections in residential areas where speed limits are exceeded and there is mixed forms of road use.</i>		
Evidence Gaps & Learning Opportunities		
<i>Speed humps have been well researched Other forms of vertical speed control are less researched Impacts on outcomes other than speed and crashes less well known</i>		
Overall Assessment		
<i>A positive traffic-calming or intervention provided applied in the correct setting. The effectiveness of the measure is greater if applied in a systematic and area wide (or at least at regular intervals along a street) manner.</i>		

#18: GATEWAYS / ENTRANCE TREATMENTS

Gateway or entrance treatments entail implementing a series of traffic engineering treatments at entrances/exits to residential or other traffic sensitive areas. These measures are generally applied on all entrances/exits or at least on the most important roads to and from these areas. These devices serve to warn motorists that they are entering a low speed or mixed traffic zone where speeds are lower and caution needs to be exercised and with the objective of reducing the number of crashes occurring in these areas. Measures include gateway treatment, speed humps, narrowings, varying pavement surfaces and colours and dynamic speed signs.

Summary of Evidence Base

Available evidence relating to the effectiveness of entrance or gateway treatments by themselves is limited and generally not of a high scientific standard. The measure must be seen as supportive to a general traffic-calming scheme or area wide treatment.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Widely applied in the Netherlands to demarcate 30 and 60 km/h zones (SWOV, 2018). These are essentially larger residential areas. They support area wide treatment and are informative to motorists.	Generally applicable to other countries and part of area wide or corridor based speed or other traffic-calming treatment	Requirements regarding the provision of such treatments/interventions in countries outside the Netherlands
Compatibility	Only compatible as part of a wider area based scheme		
Public Acceptance	It is an informative and generally non-intrusive measure that has an indirect effect of road users. It is mainly informative	It is not expected that the measure will not be acceptable to a broad base of road user	Whether or not the measure attract vandalism or misuse
Benefit–Cost Ratio	Unknown	Low BCR	
Crash & Severity Reduction	No scientific evidence	Very limited effect	
Cost-Effectiveness	Not reported	Low	
Effects on Other Road Users		Unlikely to impact negatively on road users	
Strength of Evidence			
	Strength	Notes	
Feasibility	●●○ Medium	Well documented, only feasible with area wide application of measures such as reduced speed limits	
Compatibility	●●○ Medium	Supportive of safe systems, well researched in the Netherlands, part of a package treatment	
Public Acceptance	●●○ Medium	Residents in affected areas supportive, trough traffic not. Not well documented research	
Benefit–Cost Ratio	●○○ Weak	Not well documented in consulted sources	
Crash & Severity Reduction	●○○ Weak	Not well documented in consulted sources	
Cost-Effectiveness	●○○ Weak	Not well documented in consulted sources	
Effects on Other Road Users	●●● Strong		
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		

Likely Impact in CAMBER Context
<i>Small, particularly if applied in isolation. If part of an area wide scheme, implementation in the CAMBER time frame is unlikely unless interventions are all low-cost and easily implementable within time frames. The impact of gateway treatments by themselves is unlikely to have significant impact.</i>
Evidence Gaps & Learning Opportunities
<i>The effects of gateway treatments themselves on speeds and crashes The perception and interpretation of road users of the measure/intervention The combination of physical attributes that constitute a gateway/entrance treatment and achieving the greatest effect</i>
Overall Assessment
<i>It is an essential supportive measure for area wide traffic-calming treatments. As a stand-alone intervention it is unlikely to have any significant impact on crashes, speeds or behaviour in general.</i>

#19: CHICANES OR CURB EXTENSIONS

<i>Chicanes or curb extensions create sequential horizontal deflections essentially forming an s-bend in the driven lane. Apart from narrowing the roadway they generally only allow one -way traffic but are also applied allowing two-way traffic. They are comparable to single sided road narrowing except a chicane comprises a series of narrowings. They aim to slow vehicle speeds. These physical measures increase driver attentiveness, reduce straight-line speeding, and enhance safety for pedestrians and cyclists in residential or mixed-traffic areas.</i>			
Summary of Evidence Base			
<i>The SafetyCube DSS does not report the road safety effects of chicanes by themselves. It does however report the effects of road narrowings. It is reasonable to suggest that the effect of chicanes would be similar to narrowing The results across all five studies showed that the implementation of perceptual and/or physical road narrowings reduces crash rates, vehicle speeds, and speeding vehicle numbers, and increases deceleration distances (i.e. drivers starting to decelerate further away from the intersection/crossing).</i>			
Evidence Assessment by Criterion			
	Known	Expected	Uncertain
Feasibility	Chicanes are a well-used traffic-calming treatment that is relatively easily implemented. The measure can be permanent, semi-permanent or temporary.	Easily implementable on the short term.	Integration with other low-cost interventions
Compatibility	High degree of compatibility, is supportive of safe speed principles and promotes improved	Suitable in high speed environments and as part of an area wide approach to traffic management	Compatibility with very large vehicles

	mobility for vulnerable road users in mixed road use environments		
Public Acceptance	They are generally well received by both road users and the public in general	Do not expect much resistance	Inducing risk taking behaviour among certain road users (challenge of speeding through an s-bend)
Benefit–Cost Ratio	Not reported by SafetyCube	Benefits to marginally exceed costs	
Crash & Severity Reduction	Not reported by SafetyCube	Positive effect on crashes, possibly significant effect on severity	Effect of compensating behaviour and network effect
Cost-Effectiveness	Not reported by SafetyCube	Likely to be effective	
Effects on Other Road Users	Not known		Vandalism. Maybe some reduction in available on-street parking.
Strength of Evidence			
	Strength	Notes	
Feasibility	●●○ Medium	Well documented and widely applied internationally	
Compatibility	●●● Strong	Complies with self enforcing road design, well documented	
Public Acceptance	●●● Strong	Well documented	
Benefit–Cost Ratio	●●○ Medium	Well documented	
Crash & Severity Reduction	●●○ Medium	Well documented	
Cost-Effectiveness	●●○ Medium	Well documented	
Effects on Other Road Users	●●○ Medium	Well documented	
Legend:	●●● Strong ●●○ Medium ●○● Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>Chicanes are isolated treatments and will be most effective as part of an integrated area wide approach. They are an alternative to vertical treatments (such as speed humps) but may have slightly lower impact on speeds and crashes.</i>			
Evidence Gaps & Learning Opportunities			
<i>Effect of measure on its own Most effective in combinations with (which other measures) Network effects (traffic distribution and speeding) Changes in driving behaviour</i>			

Impact on local street parking

Overall Assessment

Internationally a widely acceptable traffic-calming measure with medium to strong speed reducing impact and a potentially positive impact on crashes and crash severity. Supportive measure for reengineering the look of road environments to be less motor vehicle friendly.

#20: OPTICAL SPEED BARS (TRANSVERSE ROAD MARKINGS)

Optical speed bars (transverse road markings). Used particularly on higher-speed roads on approaches to roundabouts and some other intersections. This creates the illusion of increased speed as drivers approach hazardous areas. This visual (and possibly with noise/vibration) cue prompts drivers to slow down, improving speed compliance and reducing crash risk at curves, intersections, or approaches.

Summary of Evidence Base

Drivers are alerted to the approaching hazard. In some situations, gradually reduced spacing of bars across the lane may then provide perception of higher (increasing) speed or absence of speed reduction. Literature generally shows a small reduction in speed on approach to hazard post-implementation. This benefit can diminish over time. US research on partial transverse road markings concluded “may have some minor effects on vehicle speeds. However, the magnitude of speed reductions was generally small [...]”¹⁷

	Known	Expected	Uncertain
Feasibility	Generally feasible on high speed approaches to intersections.	Used with benefit as partial bars on approaches to bends in some countries.	
Compatibility	Possibly more effective on high-speed junction arms than at on lower speed approaches	Generally does not interfere with other measures.	Interactions with other signage may confuse.
Public Acceptance	May be objections to tyre noise “drumming” on markings		
Benefit–Cost Ratio		A relatively cheap measure to implement and so BCR likely to be >1	
Crash & Severity Reduction		Would <i>anticipate</i> modest reduction at	

¹⁷ <https://www.fhwa.dot.gov/publications/research/safety/15030/005.cfm>

		well-chosen sites – e.g. 10-20%	
Cost-Effectiveness	A relatively cheap measure to implement		Maintenance costs
Effects on Other Road Users	Potential skid hazard to motorcyclists		
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Original research since the 1980s (e.g. Helliar-Symons 1981)	
Compatibility	●●● Strong	Context specific – selecting promising sites can be a nuanced process requiring judgement	
Public Acceptance	●●○ Medium	Anecdotal, but often resistance (noise)	
Benefit–Cost Ratio	●●○ Medium	Because they are relatively cheap, most road marking measures give potential for a high positive BCR if there is <i>any</i> benefit from them	
Crash & Severity Reduction	●●○ Medium	Patchy. Many studies do not attempt quantification	
Cost-Effectiveness	●●○ <u>Medium</u>	See comments on BCR	
Effects on Other Road Users	●●● Strong	Widely held that road markings can be hazardous to motorcyclists and particularly since they are used where there is braking involved	
Legend:	●●● Strong ●●○ Medium ●○● Weak ○○● None		
Likely Impact in CAMBER Context			
<i>Likely to perform well on arms of high speed approaches to roundabouts.</i>			
Evidence Gaps & Learning Opportunities			
<ul style="list-style-type: none"> • Will the measure reduce speed? • Will the speed reduction be long-lasting? • What types of crashes do candidate sites have in the recent past (e.g. 3-5 years)? • Are recent crash histories amenable to crash reduction using transverse bars? • Would “before and after” conflict studies show a reduction? • Could they be used in conjunction with other horizontal or vertical signage? • This intervention has not been quantitatively and adequately investigated in the literature and would be a good opportunity for the CAMBER project. 			
Overall Assessment			
<i>Very popular as an intervention over a prolonged period of time. Cheap to implement. Probably unpopular if near to housing.</i>			

#21: STONE BLOCK PAVING

Stone block paving introduces a textured surface that naturally encourages drivers to reduce speed due to increased noise and vibration. It also visually differentiates low-speed or shared spaces, enhancing pedestrian priority and improving safety in residential or urban areas.

Summary of Evidence Base

There are a small number of studies that show that using stone block paving may reduce traffic speeds, heighten awareness of a pedestrian or cycling environment and be an important part of a package of interventions for speed management, traffic calming or enhancement of the public realm. On their own, they are unlikely to be sufficiently dominant in reducing crashes and hence this measure is considered here as part of speed management in urban areas.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Generally feasible in low-speed urban areas.		
Compatibility	Works well in most defined pro-pedestrian areas.		Heavy vehicles making deliveries may dislodge block paving.
Public Acceptance	Generally good. Early adoption by most towns in (for example) the UK, NL since the 1970s.	Enhances the attractiveness of urban areas.	
Benefit–Cost Ratio	Stone block paving (for example) recognised as more expensive than asphalt.		Questionable whether sufficiently dominant influential as a crash or injury reduction measure to be defined as such. Complementary to markings as measure?
Crash & Severity Reduction	Anticipated as part of wider speed management. 25-40% possible (irap.toolkit.org)		Not likely to be a crash-reducing intervention if used in isolation.
Cost-Effectiveness	Costs can be medium (to high) if expensive materials such as stone block paving is used		Maintenance – needs a good budget and supply of paving to replace dislodged stones. Anecdotal evidence is that missing blocks often replace with asphalt.

Effects on Other Road Users	If low friction surface, may increase risk to cyclists and motorcyclists.		
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	In common use worldwide	
Compatibility	●●● Strong	As above	
Public Acceptance	●●● Strong	As Above	
Benefit–Cost Ratio	●○○ Weak	Benefits include, change of texture, demarcation and visual enhancement	
Crash & Severity Reduction	●○○ Weak	Benefits include, change of texture, demarcation and visual enhancement	
Cost-Effectiveness	●○○ Weak	Benefits include, change of texture, demarcation and visual enhancement	
Effects on Other Road Users	●●○ Medium	Pay attention to friction coefficients. In town centres cyclists (and motorcyclists) may be vulnerable to slippery surfaces.	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>Urban town centres.</i>			
Evidence Gaps & Learning Opportunities			
<ul style="list-style-type: none"> • <i>Is cost likely to be an issue for some smaller municipalities? Compare options.</i> • <i>Is stone block paving more effective than using coloured surfaces?</i> • <i>Is this a beautification measure rather than a road safety intervention?</i> • <i>What are the complementary measures that are required?</i> 			
Overall Assessment			
<i>Stone block paving may be seen as some of the detail in a successful speed management or traffic calming scheme. It can have a role in beautification of the environment. On its own, this intervention does not exert huge influence on casualty reduction, but it should have good effect and provide an effective and attractive finish when combined with other measures.</i>			

#22: COLOURED SURFACING (CONFLICT ZONES, CYCLING PATHS)

Coloured surfaces used to visually differentiate conflict zones, often cycling paths, from general traffic lanes. Also used for marking out higher-risk spaces such as intersections. This intervention enhances user awareness and delineates priority or high-risk areas, improving visibility and driver compliance. It is a low-cost measure that often supports safer interactions between motor vehicles and vulnerable road users.

Summary of Evidence Base

Elvik et al. (2009) identify three evaluations of the use on cycle routes. The Dutch Cycling Embassy (2024) provides more detail and reference to the CROW Design Manual for Bicycle Traffic. A Bloomberg study of 17 locations found improvements at junctions featuring artistic or colourful road markings – “Asphalt Art Study Safety”, Schwartz (2022).

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Possible if part of a larger cycling package, or, for example, urban renewal at junctions.		Space requirements, political motivation.
Compatibility		Generally no conflict with (for example) black asphalt.	Is colour blindness ever an issue?
Public Acceptance	Supported if pro-cycling public and political acceptance.		Do the public enjoy the colour, (or the intrusion or the art in those contexts?)
Benefit–Cost Ratio	Modest positive BCR if introduced to cover an existing cycle route		
Crash & Severity Reduction	Elvik <i>et al.</i> report a significant reduction of cycle accidents was found at junctions coloured cycle lanes. One study shows a reduction of 22% in cyclist collisions. Bloomberg study at junctions found 37% reduction in injury crashes.	Danish work shows coloured cycle lanes are most favourable in non-complex junctions and may have detrimental effects in complex junctions (Elvik <i>et al.</i>)	Cycling crash current situation and reduction difficult to monitor because of under-reporting
Cost-Effectiveness	The inclusion of red (for example) pigment increases asphalt cost by 40%, but only by 20% if the top few centimetres are coloured.		Maintenance and renewal costs
Effects on Other Road Users	Ensure good surface friction not compromised by colouring.	Clearly demarcated cycle paths should be helpful to other road users	
Strength of Evidence			
	Strength	Notes	

Feasibility	●●● Strong	See Dutch, Danish & New York experience.
Compatibility	●●● Strong	See Dutch, Danish & New York experience.
Public Acceptance	●●● Strong	See Dutch, Danish & New York experience.
Benefit–Cost Ratio	●○○ Weak	
Crash & Severity Reduction	●●○ Medium	Not much evidence from the cycling studies but the Bloomberg work has encouraging results.
Cost-Effectiveness	●●○ Medium	If part of ongoing maintenance
Effects on Other Road Users	○○○ None	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>Demarcate existing or new cycle lanes or urban areas high in potential conflict points</i>		
Evidence Gaps & Learning Opportunities		
<ul style="list-style-type: none"> • <i>Would conflict analysis provide answers to the benefits of these measures?</i> • <i>Do the interactions of motorised vehicles with cycles and between pedestrians and cyclists change?</i> 		
Overall Assessment		
<i>For cyclists, this provides the opportunity for territory to be marked out and potentially for conflicts to be reduced. Evidence on when and where to use it is scarce, but countries with well-established cycling programmes show that it is a substantial tool in establishing cyclists as co-equal road-users.</i>		

#23: NARROWING LANE WIDTH VIA MARKINGS (EDGE LINES OR CENTERLINE SHIFTS)

<i>Narrowing lane width via markings (edge lines or centerline shifts): Narrowing lane width using edge lines or centerline shifts visually reduces the perceived roadway width, prompting drivers to slow down. This low-cost measure enhances driver attention, discourages overtaking, and improves safety for pedestrians and cyclists without major infrastructure changes.</i>			
Summary of Evidence Base			
<i>SafetyCube results show that implementing road narrowings overall reduces accident rates, reduces vehicle speeds and increases deceleration distances. According to the Crash Modification Factors Clearinghouse, the installation of lane narrowing through rumble strips and painted median at rural stop-controlled approaches reduces crashes by 31%.</i>			
Evidence Assessment by Criterion			
	Known	Expected	Uncertain
Feasibility	iRAP and SafetyCube categorize lane narrowing as a low-cost intervention with high feasibility.	Likely feasible during marking or resurfacing. Possible conflict with existing regulations, if	Durability under winter maintenance and aesthetic restrictions is not documented.

	They are deployed without geometric changes. Installation is possible within routine maintenance, by standard paints/thermoplastics. Not applicable to high speed roads.	centreline shifts allow overtakings.	
Compatibility	Are commonly compatible with common road-asset inventories and signing strategies used by road authorities.	Expected to integrate with CAMBER's digital-twin and data-management layers.	Uncertain when applied in environments with high visual complexity. Driver (cognitive) workload
Public Acceptance	Not known		
Benefit–Cost Ratio	Not known	Likely to be higher than 1, but not an extremely high ratio	Cost of construction and maintenance in pilot countries
Crash & Severity Reduction	Significant reductions in accident rates were found (Crash Modification Factors Clearinghouse).	Expected reductions in approach speed.	Maintenance and retroreflective degradation vary.
Cost-Effectiveness			Lifecycle cost/incremental safety gain not documented.
Effects on Other Road Users	Significant reduction in speeds		
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Widely applied and used internationally	
Compatibility	●●○ Medium	Compatible with pilots and safe systems (self explaining) concepts	
Public Acceptance	●○○ Weak	Increases workload and ADAS warnings, well documented	
Benefit–Cost Ratio	●●○ Medium	Reasonably well documented in consulted sources	
Crash & Severity Reduction	●●○ Medium	Reasonably well documented in consulted sources	
Cost-Effectiveness	●●○ Medium	Reasonably well documented in consulted sources	
Effects on Other Road Users	●○○ Weak	Not known	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		

Likely Impact in CAMBER Context
<i>Narrowing lane width via markings can improve safety on urban collector streets</i>
Evidence Gaps & Learning Opportunities
<i>Effect on the number of crashes and the severity of injuries Cost effectiveness BCR</i>
Overall Assessment
<i>Limited evidence has been found in the consulted sources, but nonetheless this intervention shows some potential for the pilots.¹⁸ VRU and operational uncertainties create opportunities for CAMBER evaluation.</i>

#24: PERIPHERAL MARKINGS TO SIMULATE NARROWING EFFECT (OPTICAL NARROWING / PAINTED LANE NARROWING)

<i>Peripheral Markings to Simulate Narrowing Effect (Optical Narrowing / Painted Lane Narrowing)</i>			
Summary of Evidence Base			
<ul style="list-style-type: none"> <i>iRAP and SafetyCube show that lane narrowing, edge markings, and enhanced delineation all contribute to speed reduction and better lane discipline. The optical narrowing intervention uses the same perceptual mechanism.</i> <i>FHWA materials confirm that pavement-based visual cues before and through hazardous sections (curves, transitions) can reduce speeds and lane departures. (CMF=0.68 Old study, ½ stars quality. (Griffin & Reinhardt, 1996)</i> <i>Dirección-General de Tráfico uses painted perceptual treatments, including varied edge markings and optical warnings on secondary roads, though no formal crash evaluation is available.</i> <i>The Handbook of Road Safety emphasizes the role of driver perception, preview time, and visual guidance in reducing speed and improving stability on rural roads, providing conceptual support for optical narrowing.</i> 			
Evidence Assessment by Criterion			
	Known	Expected	Uncertain
Feasibility	Marking-based curve and edge treatments are widely feasible and used in routine maintenance (iRAP, FHWA).	Likely feasible on secondary roads with good pavement condition.	Durability under winter wear and on narrow shoulders is not documented.
Compatibility	Aligns with Safe System-based	Compatible with digital inventories and route treatments.	Unknown effects on cyclists, tactile surfaces, and AV lane detection.

¹⁸ Beside the consulted sources, which are based on results across multiple studies, some individual studies indicate the potential for this intervention (e.g. Pirdavani et al., 2025; Havránek et al., 2020; Garach et al., 2022). Note: only the sources mentioned in Section 3 have been used to assess the interventions in this Annex to ensure a consistent approach.

	delineation strategies (iRAP, SafetyCube).		
Public Acceptance	Road markings and perceptual cues are generally accepted, non-intrusive.	Likely acceptable on high-speed approaches needing speed reduction.	No studies on cyclist/motorcyclist perception or visual clutter concerns.
Benefit–Cost Ratio	Marking upgrades are low-cost with good BCR in general (iRAP, SafetyCube).	Expected favourable BCR if used at high-risk speeding locations.	No direct cost or effect data for optical narrowing.
Crash & Severity Reduction	Enhanced curve/edge markings reduce run-off-road crashes (FHWA).	Expected modest speed reduction and better lane keeping.	No CMF or before–after data for optical narrowing specifically. Effect in the long run unknown.
Cost-Effectiveness	Marking-based measures are inexpensive and scalable.	Likely cost-effective where speeding is dominant crash factor.	Renewal frequency and incremental benefit unknown.
Effects on Other Road Users	Better delineation improves predictability for all users (iRAP).	Could reduce overtaking conflicts and sudden braking.	Effects on cyclists/motorcyclists, especially with reduced visual space, unknown.
Strength of Evidence			
	Strength	Notes	
Feasibility	●●○ Medium	Not widely applied and documented but used internationally	
Compatibility	●○○ Weak	Compatible with pilots and safe systems (self explaining) concepts	
Public Acceptance	●●○ Medium	Increases workload and ADAS warnings,	
Benefit–Cost Ratio	●●○ Medium	Reasonably well documented in consulted sources	
Crash & Severity Reduction	●○○ Weak	Reasonably well documented in consulted sources	
Cost-Effectiveness	●●○ Medium	Reasonably well documented in consulted sources	
Effects on Other Road Users	●●○ Medium	Not known	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>Most likely to be effective on:</i>			
<ul style="list-style-type: none"> • rural or semi-rural high-speed approaches, • secondary roads with recurrent lane-departure crashes, 			

- segments where actual lane width is adequate, but drivers perceive the road as wide and comfortable,
 - areas needing speed reduction without geometric change.
- Effectiveness is expected to be highest where current markings and delineation are weak, worn, or inconsistent.

Evidence Gaps & Learning Opportunities

- While a reduction in high-end speeding was observed, the sources do not extensively discuss the long-term effectiveness of purely optical narrowing without physical measures, as driver adaptation can potentially diminish the long-term safety benefits.
- Studies related to crashes and before-and-after speed measurements for coloured, patterned, or peripheral-line optical illusions are not widely carried out in these sources.
- Interaction with cyclists, motorcyclists, visually impaired users, and AV systems needs more attention.
- Maintenance requirements, durability, and performance during rain/night conditions are untested.
- CAMBER pilots might be able to collect valuable data on: speed profiles, lateral lane position and driver approach behaviour.

Overall Assessment

Peripheral markings to simulate a narrowing effect (painted narrowing) is an effective speed management technique, particularly useful for transitioning drivers from high-speed interurban sections into slower built-up areas, functioning as a "gateway". By reducing the perceived lane width, it achieves desirable driver behaviour, including speed reduction (up to a 45% reduction in high-speed drivers in some cases).

This intervention is aligned with the visual-guidance and speed-management principles recognized by iRAP and SafetyCube, as well as the Handbook of Road Safety. Evidence exists for the mechanism (speed reduction through perceptual cues and lane narrowing), but not directly for this specific treatment. As such, the intervention has a strong conceptual basis but a weak empirical foundation.

#25: CYCLE LANES WITH VISUAL SEPARATION (PAINT OR COLOUR)

Cycle lanes use painted lines or coloured surfacing to clearly distinguish the cycling space from motor vehicle lanes. This intervention increases the visibility of cyclists, encourages drivers to maintain lateral distance, and promotes safer interaction without requiring physical barriers.

Summary of Evidence Base

According to the SafetyCube DSS, the installation of a cycle lane may have a positive or negative effect on road safety. A not physically separated cycle lane could reduce injury accidents for cyclists. The effect is greatest at road intersections. On the other hand, a physically separated cycle track may increase the number of accidents, particularly cycle accidents at intersections. The results are however not statistically significant and as a rule separated cycle paths are safer than cycle lanes.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
--	-------	----------	-----------

Feasibility	Cycle lanes are widely used in many countries and the effects vary from slightly to very effective	It is expected that road safety will improve when implementing cycle lanes on roads where cycling occurs and there are presently no cycle lanes	Scale and continuity of routes
Compatibility	Separating or segregating heavy motorized traffic from cyclists is good for safety and complies with safe system practice	Good fit on roads with cycling traffic	Discipline of cyclists within cycle lanes
Public Acceptance	Generally high	Likely to be high. Shifts the balance of public policy priorities and gives encouragement to less confident cyclists	Reaction of motorists in environments without high levels of cycling infrastructure
Benefit–Cost Ratio	Not known in SafetyCube (https://www.roadsafety-dss.eu/#/)	Likely to be higher than 1 but not an extremely high ratio	Cost of construction and maintenance in pilot countries without cycling experience, or with limited experience
Crash & Severity Reduction	Generally effects on crashes are not significant	Decrease in crashes involving cyclists after introduction of cycle lanes	The size and significance of the effect
Cost-Effectiveness	Unknown	Likely to be effective, particularly in countries where construction costs are relatively low	Non-safety benefits in encouraging modal transfer
Effects on Other Road Users		Reduced speeds	Behaviour of motorized traffic toward cyclists
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Well documented and feasible as a first form of segregation of motorised and non-motorised traffic	
Compatibility	●●● Strong	Compatible where cycling is a strong mode. Supports first safe system principles	
Public Acceptance	●●● Strong	Well documented	

Benefit–Cost Ratio	●○○ Weak	Not well documented in consulted sources
Crash & Severity Reduction	●○○ Weak	Not well documented in consulted sources
Cost-Effectiveness	●○○ Weak	Not well documented in consulted sources
Effects on Other Road Users	●●● Strong	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>Cycle lanes will perform well in situations where cycling is prevalent but where there are no separate facilities.</i>		
Evidence Gaps & Learning Opportunities		
<i>Costs (construction, maintenance, operating) and benefits (travel time, crashes, delays etc). Notoriously difficult to evaluate benefits of individual schemes despite developments in assessment techniques over recent decades.</i>		
Overall Assessment		
<i>An internationally well used intervention promoting healthy mobility and (depending on the application) supporting safe system (safe speed) principles. It offers opportunities for countries developing a cycling culture. However, evaluating benefits is difficult despite development in evaluation techniques over recent decades.</i>		

#26: REFUGE ISLANDS AT CROSSINGS (OR “REFUGE IN MARKED CROSSWALK”).

Refuge islands at crossings (or “Refuge in marked crosswalk”). Elvik et al. (2009) describe it thus: “A refuge in marked crosswalk is a raised (kerbed) median that separates the two directions of vehicle traffic flow, which may be used by pedestrians to cross in two stages. A refuge also shortens the distance that has to be crossed by pedestrians in each crossing stage, and vehicle traffic has to be observed from only one direction” Apart from providing a safe waiting area in the middle of the road for pedestrians who cannot cross the entire road in one go, it improves crossing safety by reducing exposure time to traffic, slowing vehicle speeds, and enhancing pedestrian visibility.

Summary of Evidence Base

From Elvik et al: “The installation of marked crosswalks with refuge at locations where there previously was no marked crosswalk was not found to change the number of accidents. This result is based on only two studies that have not controlled for vehicle or pedestrian volumes. When refuges are installed in existing marked crosswalks, pedestrian accident rates were found to decrease, while vehicle accident rates were found to increase. Both results refer to accident rates and both vehicle and pedestrian volumes are taken into account. None of the results is statistically significant.”

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Elvik et al – treats refuges as standard	Likely to be feasible in many situations	

	design tools with no unusual feasibility constraints. SafetyCube DSS categorises refuge islands under standardised crossing aids used widely without major geometric works.	unless road width insufficient to accommodate larger vehicles.	
Compatibility		Simply installing a refuge on higher-speed roads unsuitable because of potential risk to pedestrians. Complementary measures necessary.	What are the demand lines for pedestrians at pilot sites?
Public Acceptance	ties.	Usually a popular addition for local communities	Delay to other road users
Benefit–Cost Ratio	Elvik <i>et al.</i> assume (installing a refuge at existing crossing) gives a 25% reduction in crashes and show BCR of 4.5 for AADT of 5,000, but lower at lower AADT.		
Crash & Severity Reduction	Elvik <i>et al.</i> say reduction in pedestrian collisions and increase in vehicle crashes when compared with ordinary marked crossing. irap.toolkit.org suggests a reduction of 25-40% in casualties and a low-medium cost		
Cost-Effectiveness	See comments on BCR		
Effects on Other Road Users	Delay to non-pedestrian road users. Potential increase in shunt crashes		

Strength of Evidence		
	Strength	Notes
Feasibility	●●● Strong	
Compatibility	●●○ Medium	Suitable at locations where pedestrians relatively common and vehicle speeds low
Public Acceptance	●●● Strong	Often popular with/requested by local communities
Benefit–Cost Ratio	●○○ Weak	Elvik <i>et al.</i> comment that results not statistically significant
Crash & Severity Reduction	●●○ Medium	As above
Cost-Effectiveness	●●○ Medium	As above
Effects on Other Road Users	●●● Strong	Interruption of flow leading to shunt crashes
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>Intervention likely to perform well when there is good compliance from drivers, the refuge is situated on a road that is not excessively wide, and when vehicle speeds are respectful of the presence of pedestrians.</i>		
Evidence Gaps & Learning Opportunities		
<p><i>The benefit of most pedestrian measures is under-researched and difficult to prove for individual interventions. This is in part due to the absence of satisfactory exposure data.</i></p> <ul style="list-style-type: none"> <i>How does risk reduction compare if refuge installed where there is no existing crossing?</i> <i>Is there sufficient storage on the refuge if pedestrian activity is high?</i> <p><i>Professional and engineering judgement is often required to assess the suitability of a site for a new pedestrian refuge or for provision of a refuge on an existing location.</i></p> <ul style="list-style-type: none"> <i>Are there situations in which provision of a refuge will increase risk?</i> <i>Will the crossing and refuge simply focus a dispersed risk at one location?</i> <i>Does the refuge and crossing (or more than one crossing) encourage increases in vehicle speeds between crossings as opposed to slower, more considerate speeds if it is a pedestrian space-sharing environment?</i> <p><i>Consider using complementary measures that increase visibility of the refuge and highlight to drivers and riders that it is there.</i></p> <ul style="list-style-type: none"> <i>What are the ideal set of complementary interventions?</i> <i>Should speed management be part of these measures?</i> 		
Overall Assessment		
<i>A potentially useful pro-pedestrian measure in the right place. Can reduce pedestrian casualties, but likely to increase vehicle crashes. Statistical evidence for injury reduction is not strong but they can be part of enhancing the “safe-feel” environment. CAMBER could conduct conflict studies to examine relevant factors.</i>		

#27: RAISED PEDESTRIAN CROSSING

Raised crossing: A raised crossing (or raised pedestrian/zebra crossing) is a pedestrian crossing placed on a raised platform (typically a trapezoidal speedhump) at the same height as the adjacent footpath. The elevation forces vehicles to slow down, improves pedestrian visibility, and emphasises pedestrian priority while maintaining step-free access.

Summary of Evidence Base

Raised crossings slow motor vehicles and enhance pedestrian visibility. Evidence (Elvik et al., 2009; SafetyCube) shows strong reductions in speed and pedestrian injury risk. The iRAP Toolkit emphasises benefits when combined with zebra markings and lighting. Impacts on cyclists and motorcyclists depend on ramp profiles.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Feasible on ≤50 km/h roads; requires proper drainage.	Suitable on most urban collector streets.	Suitability on bus or emergency routes.
Compatibility	Fits pedestrian-priority and traffic calming strategies.	Good fit where pedestrian activity is high.	Compatibility with cycle-heavy environments.
Public Acceptance	Generally high for local communities.	Drivers may accept over time.	Acceptance for cyclists, buses, motorcycles.
Benefit–Cost Ratio	High in pedestrian crash areas.	Good Return on Investment (ROI) as a traffic calming measure. If similar to speed humps, speed humps which SafetyCube suggests to have a BCR (best estimate) of 18,2 based on inj. crash reduction only. Accidents(fatal,serious,slight) reduction: 17% Implementation cost: 3,836 EUR /speed hump	Lifecycle costs. Road Safety Toolkit has this as a medium cost measure lasting 5-10 years.
Crash & Severity Reduction	Road safety Toolkit: 40-60% injury reduction.	Increased yielding.	VRU interactions.
Cost-Effectiveness	Cost-effective for pedestrian risk, but not traffic operations (increased stops and delays).	Effective for speed reduction and yielding on low-speed roads (<=50km/h) with high pedestrian flows.	Maintenance burden.
Effects on Other Road Users	Slows vehicles; neutral for pedestrians.	Expected safety benefit for pedestrians.	Uncertain for buses and may add to noise. Impacts on disability access (those in

			wheelchairs or mobility vehicles should benefit due to reduced ramps, but the impact on sight impaired pedestrians is not known.
Strength of Evidence			
	Strength	Notes	
Feasibility	●●● Strong	Relatively low-cost measure on lower order roads, see also speed humps	
Compatibility	●●○ Medium	Compatible where VRU and motorised traffic mix and speeds have to be kept low	
Public Acceptance	●●○ Medium	Reasonably well documented, generally high	
Benefit–Cost Ratio	●●○ Medium	Reasonably well documented	
Crash & Severity Reduction	●●● Strong	Well documented	
Cost-Effectiveness	●●○ Medium	Reasonably well documented	
Effects on Other Road Users	●○○ Weak		
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None		
Likely Impact in CAMBER Context			
<i>Strong performance in pedestrian-heavy, moderate-speed environments; less appropriate for heavy-vehicle routes.</i>			
Evidence Gaps & Learning Opportunities			
<ul style="list-style-type: none"> - VRU-specific impacts (cycling/motorcycling) - Long-term cost data - Performance under winter conditions 			
Overall Assessment			
<i>A well-evidenced measure with strong pedestrian safety benefits. VRU and operational uncertainties create opportunities for CAMBER evaluation.</i>			

#28: ZEBRA CROSSINGS WITH ADVANCE YIELD MARKINGS (UNRAISED PEDESTRIAN CROSSING WITH AND W/O REFUGE ISLAND)

Two types are dealt with, level pedestrian crossings with advance warning and yield markings and regular zebra crossings.

Level pedestrian crossings (Zebra crossings) with advanced yield markings place stop or yield lines before the crossing to create additional buffer space between vehicles and pedestrians. This

design improves pedestrian visibility, reduces encroachment onto the crossing, and increases driver compliance and yielding behaviour.

Marked crosswalks or zebra crossings are places designated for pedestrians to cross a road. Crosswalks can be marked with paint, thermoplastic materials or plastic tape, among other materials. Marked crosswalks generally assist, and usually prioritise pedestrians, depending on the locality. Providing marked crosswalks is aimed at making it easier and safer for pedestrians to cross the road.

Summary of Evidence Base

According to the SafetyCube DSS, the safety impact of marked crosswalks is unclear, especially the impact on pedestrian crash rate. Some studies find no significant effects on the number of crashes, while some find significant increases in the number of crashes at some locations or for some groups of road users. However, a significant reduction in crash severity is consistently found in literature.

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Best applied at intersections or lower order urban roads with lower speed limits		Suitability on high speed roads, from Safe systems perspective unwanted
Compatibility	Provided crossings are applied on low speed roads, supports pedestrian mobility	Good fit where pedestrian activity is high.	Compatibility with cycle-heavy vehicle environments.
Public Acceptance	Generally high among vulnerable road users	Drivers may accept over time.	Acceptance for cyclists, buses, motorcycles.
Benefit–Cost Ratio	Uncertain, small		
Crash & Severity Reduction	No marked effect on crash number but crash severity is reduced	Less yielding for pedestrians	More conflicts between NMT and traffic
Cost-Effectiveness	Cost-effective for pedestrian risk.	Limited	Maintenance burden. Visibility and lighting
Effects on Other Road Users	Improves liveability for elderly. Presence of crossings in urban areas heightens awareness of drivers and riders to pedestrians	Expected safety benefit for pedestrians. Supports mobility	

Feasibility	●●○ Medium	
Compatibility	●●○ Medium	
Public Acceptance	●●○ Medium	
Benefit–Cost Ratio	●○○ Weak	
Crash & Severity Reduction	●○○ Weak	
Cost-Effectiveness	●○○ Weak	
Effects on Other Road Users	●●○ Medium	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>Pedestrian crossings at intersections and midblock on low speed roads and on pedestrian desire lines can significantly improve mobility and safety on high demand pedestrian routes.</i>		
Evidence Gaps & Learning Opportunities		
<i>Effect of crossings on Conflicts, not yielding vehicles, effect on numbers of crashes versus effect on injuries CBA and effectiveness.</i>		
Overall Assessment		
<i>An intervention with potential at intersections or midblock on low-speed roads where speeds are also certain to be low. Effectiveness is mixed due to the research covering many conditions. More likely to be effective if used with complementary speed-reducing measures.</i>		

#29: IN-GROUND LIGHTING FOR PEDESTRIAN CROSSING

Embedding LED lights into the pavement to illuminate the crossing area when pedestrians are present or during low-light conditions. This intervention enhances the pedestrian crossing visibility, increases driver awareness, and improves safety at night or in poor weather.

Summary of Evidence Base

- *Elvik's handbook claims that poor visibility is an important contributor to pedestrian crashes, especially at night and during poor weather. Any measure that increases conspicuity reduces late detection of pedestrians.*
- *Lighting upgrades at crossings are recognised as effective in reducing nighttime crashes; in-ground LEDs use the same visibility mechanism but are not evaluated directly in the required sources.*
- *Evidence gaps include absence of CMFs, unknown durability and maintenance cycles, uncertainty about glare or distraction, and no established evaluations in Europe.*

Evidence Assessment by Criterion

	Known	Expected	Uncertain
Feasibility	Lighting improvements at crossings are feasible and commonly applied.	Expected to be feasible where electrical infrastructure exists or can be added at reasonable cost.	Installation complexity increases on rural roads without power supply; maintenance of

		Installable w/o major geometric changes.	embedded LEDs is uncertain.
Compatibility	Crosswalk visibility enhancements and lighting improvements are commonly supported.	Likely compatible with CAMBER digital inventories, pedestrian detection systems, and visibility improvement strategies.	Compatibility with national regulations on embedded lighting, temporary blinding risk, or potential conflicts with tactile paving is not established.
Public Acceptance	Lighting at crossings is generally accepted and often requested by communities.	Expected high acceptance as the intervention directly enhances pedestrian visibility.	Acceptance of embedded flashing LEDs is unknown; concerns about glare, light pollution, or aesthetics may arise.
Benefit–Cost Ratio	No effectiveness studies available on this specific lighting approach	Expected positive BCR if in-ground lighting reduces nighttime pedestrian conflicts and improves recognition.	
Crash & Severity Reduction	Lighting, in general, at crossings reduces nighttime crashes by increasing detection time and conspicuity.	Expected reduction in pedestrian crash risk through earlier driver recognition and speed adaptation under low-light conditions.	No CMFs or before–after studies for in-ground lighting
Cost-Effectiveness	Lighting-related pedestrian measures are described as cost-effective in SafetyCube.	Could be cost-effective in high-risk nighttime crossing locations with poor ambient lighting.	Lifecycle cost, LED durability, and maintenance of embedded components are uncertain.
Effects on Other Road Users	Visibility improvements generally benefit vulnerable users by making conflict points more predictable (SafetyCube, iRAP).	Likely to help older pedestrians, children, and cyclists who rely heavily on crossing conspicuity.	Potential glare, confusion for cyclists, or masking of informal desire lines not assessed; effects on visually impaired users unknown.
Strength of Evidence			
	Strength	Notes	
Feasibility	●○○ Weak	Dependant on power supply, susceptible to maintenance, not well documented	
Compatibility	●○○ Weak	Supports safe systems measures, not well used in less developed and populated areas	
Public Acceptance	●○○ Weak	Not known	
Benefit–Cost Ratio	●○○ Weak	Not well documented in current sources	

Crash & Severity Reduction	●○○ Weak	Not well documented in current sources
Cost-Effectiveness	●○○ Weak	Not well documented in current sources
Effects on Other Road Users	●○○ Weak	Not well documented in current sources
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<p><i>The intervention is likely to perform better in:</i></p> <ul style="list-style-type: none"> • <i>nighttime high-conflict crossings,</i> • <i>low-ambient-light rural and secondary road segments,</i> • <i>locations where overhead lighting is ineffective, absent, or impractical;</i> • <i>crossings with high pedestrian vulnerability (children, elderly, multimodal users).</i> 		
Evidence Gaps & Learning Opportunities		
<ul style="list-style-type: none"> • <i>Unknown long-term durability under European winter conditions, snowplough activity, and moisture ingress.</i> • <i>Empirical studies on glare, driver distraction, behavioural adaptation, or interactions with ADAS.</i> • <i>CAMBER pilots might be able to gather evidence on:</i> <ul style="list-style-type: none"> ○ <i>nighttime and adverse-weather speed profiles,</i> ○ <i>stopping sight distance improvements,</i> ○ <i>mixed lighting environments,</i> ○ <i>maintenance needs.</i> 		
Overall Assessment		
<p><i>In-ground LED lighting for pedestrian crossings is consistent with the core visibility-enhancement mechanisms identified by all sources. Although the intervention is intuitively strong and conceptually aligned with documented crash mechanisms, it lacks direct empirical evaluation in all required sources. CAMBER might be able to provide unique, high-value evidence by piloting and rigorously monitoring this technology under real-world conditions.</i></p>		

#30: WARNING SYSTEM FOR PEDESTRIANS CROSSINGS

<i>Warning systems for pedestrian crossings have a camera detecting pedestrians and showing a warning message on VMS to motorists warning of a pedestrian wanting to cross</i>			
Summary of Evidence Base			
<i>There are many studies on reporting positive effects of this sort of advanced pedestrian crossing system. However, SafetyCube and other resources reporting metastudies and generalised effects do not provide results on this specific measure</i>			
Evidence Assessment by Criterion			
	Known	Expected	Uncertain
Feasibility	Deployed in many countries internationally, both in signalised and	Preferable in locations with	Implication for power supply in

	unsignalised applications (see for instance https://highways.dot.gov/safety/proven-safety-countermeasures/rectangular-rapid-flashing-beacons-rrfb).	higher volumes of pedestrians.	remote locations, costs and availability to use in pilots Uncertain of effects of too many warnings on motorists (risk of ignoring message and making system redundant)
Compatibility		Facilitates improved and potentially safer pedestrian crossing	
Public Acceptance	Uncertain	Likely to be high	Risk of pseudo-security
Benefit–Cost Ratio	Uncertain in Europe	Expected that benefits marginally outweigh costs	
Crash & Severity Reduction	According to FHWA 47% reduction in pedestrian crashes	Marginally positive (fewer VRU crashes)	
Cost-Effectiveness	Cost-effective	Marginally effective, high cost and maintenance intensive	
Effects on Other Road Users	Heightened awareness motorists	Drivers ignore the VMS, too many warnings, balance between system being active and effective versus inactive and ineffective	
Strength of Evidence			
	Strength	Notes	
Feasibility	●●○ Medium	Dependant on power supply, used in poor visibility locations	
Compatibility	●●○ Medium	Supportive system to emphasize dangerous location	

Public Acceptance	●●○ Medium	Not well documented
Benefit–Cost Ratio	●○○ Weak	Not well documented
Crash & Severity Reduction	●●○ Medium	Not well documented
Cost-Effectiveness	●●○ Medium	Reasonably well documented
Effects on Other Road Users	●●○ Medium	
Legend:	●●● Strong ●●○ Medium ●○○ Weak ○○○ None	
Likely Impact in CAMBER Context		
<i>Warning systems for pedestrians crossings have application in CAMBER, particularly pilots where pedestrians crossing roads are regularly not given priority to cross because they are not seen or not given right of way. Could improve crossing opportunity but care needed to exclude risk of pseudo-security</i>		
Evidence Gaps & Learning Opportunities		
<i>Effect on speeds and driver yielding behaviour Reliability Degree of pseudo-security</i>		
Overall Assessment		
<i>A measure with potential in CAMBER pilots, although there is little European evidence of efficacy. In America, similar devices are positively received. If we assume similar effects of these warning systems as for VMS and slow down signs results could be promising (e.g. Hussain et al., 2023)</i>		

ANNEX 3: DATA DICTIONARY

A data dictionary is a structured reference that defines each data element used in CAMBER: what it represents, how it is measured, where it comes from, and how it can be used.

The data dictionary is essentially a “metadata catalogue”. It is a catalogue about the data that ensures everyone in the consortium is using the same definitions, formats, and units when collecting, exchanging, and analysing data.

The data dictionary is a living reference system that defines how CAMBER’s data is described, shared, and evaluated. It underpins the Evaluation Framework by turning diverse datasets into a coherent and comparable evidence base, ensuring that the results of CAMBER’s testing activities can be meaningfully compared and integrated into the broader impact analysis.

Purpose in the CAMBER Evaluation Framework

The data dictionary will:

- Standardise terminology across pilots, partners, and systems.
- Define measurement protocols (what, when, how often, and with what precision).
- Support integration between diverse data sources (e.g. telematics, digital twins, road sensors, simulator outputs).
- Enable repeatability and comparability of evaluations across countries and environments.
- Facilitate linkage between the Evaluation Framework and later analyses such as cost-benefit and impact modelling under Task 2.4.

Typical Structure of a Data Dictionary Entry

Each variable or dataset is described as a record containing metadata fields.

Field	Description	Example (CAMBER context)
Variable Name	Unique short name or code used in datasets.	road_surface_roughness
Definition / Description	What the variable measures, including context and relevance.	Average deviation of pavement surface texture measured by probe vehicle or RoadLab system.
Data Source	Origin of the data (partner, sensor, simulation, external provider).	AIT RoadLab, BMOB telematics feed
Unit of Measurement	The measurement unit.	mm, or IRI (International Roughness Index)
Data Type	Numeric, categorical, Boolean, text, timestamp, etc.	Numeric
Measurement Frequency	How often data are collected or updated.	Continuous (real-time), or annual survey
Spatial Resolution	Geographic granularity (e.g. per 10 m segment, per road section, per junction).	10 m section
Temporal Resolution	Time window covered by each measurement.	Daily averages

Collection Method / Instrument	How and with what tool or technology the data are obtained.	Accelerometer sensor on probe vehicle
Validation / QA method	How the accuracy and reliability are verified.	Comparison with ground-truth data (LIDAR survey)
Data Storage / Format	File type or database structure.	CSV, GeoJSON, PostgreSQL
Data License / Access Level	Internal, open, restricted, proprietary.	Internal consortium use
Linked Indicators	Evaluation metrics or KPIs that use this variable.	Safety Performance Indicator (SPI 3), Star Rating model input
Notes / Comments	Any special conditions or assumptions.	Data unavailable in winter months

COMPONENT 1: SAFETY-INTEGRATED MAINTENANCE SYSTEMS AND PROCESSES

Variable Name	maintenance_record_id	Data Source	Road authorities
Data Type	Text	Unit	ID
Frequency	Per intervention	Spatial Resolution	Road section
		Linked Indicators	Efficiency KPI
Definition / Description	Unique identifier linking maintenance and safety data.		
Collection Method	Manual record entry based on meetings with road authorities or GPS-based alignment of safety and road condition data.		
Validation / QA	Cross-check with work orders		
Notes / Info Needed	Define ID structure.		

Variable Name	safety_risk_index	Data Source	Road safety assessment, telematics
Data Type	Numeric	Unit	0-100
Frequency	Annual	Spatial Resolution	100m road segments
		Linked Indicators	SPI 3
Definition / Description	Combined safety risk score (crash probability × severity).		
Collection Method	Data collected according to the iRAP Star Rating safety assessment methodology. 1. Road survey in accordance with this guide 2. Road coding in accordance with this guide and structured following this specification 3. Analysis and reporting in accordance with this guide		
Validation / QA	Third party quality assurance of road coding data will be carried out for at least a 10% representative sample of the roads assessed. The road safety risk scores will be compared with crash data for validation.		
Notes / Info Needed	Define normalisation method.		

Variable Name	maintenance_response_time	Data Source	Pilot authority logs
Data Type	Numeric	Unit	Days / Weeks
Frequency	Ongoing	Spatial Resolution	Site-level
		Linked Indicators	Efficiency indicator
Definition / Description	Time between detection and intervention completion.		
Collection Method	Maintenance logs		
Validation / QA	Comparison of citizens complaints and vs RA's field records (valid only for detection)		

Notes / Info Needed	Define acceptable delay (this will depend on the type of defect and level of distress).
---------------------	---

Variable Name	safety_integration_score	Data Source	Survey / interview
Data Type	Categorical	Unit	% / qualitative
Frequency	End of pilot	Spatial Resolution	Organisation-level
		Linked Indicators	Process KPI
Definition / Description	Degree of integration between asset and safety management systems.		
Collection Method	Questionnaire based on meetings with road authorities.		
Validation / QA	Partner review		
Notes / Info Needed	Development of scoring template is required.		

Variable Name	asset_condition_score	Data Source	RoadLab / inspection
Data Type	Numeric	Unit	0–5
Frequency	Annual	Spatial Resolution	Segment
		Linked Indicators	Asset KPI
Definition / Description	Condition rating for road assets (surface, signage, markings). Surface being collected by RoadLAB or from external partners. Signage and markings to be seen at the site		
Collection Method	Sensor/visual inspection		
Validation / QA	QC vs photographic records		
Notes / Info Needed	Confirm scale.		

COMPONENT 2: NEW-GENERATION DATA SOURCES

Variable Name	data_source_id	Data Source	Project registry
Data Type	Text	Unit	ID
Frequency	Once	Spatial Resolution	Dataset-level
		Linked Indicators	Data quality indicator
Definition / Description	Unique identifier for each dataset type (vehicle, sensor, satellite) depending on outputs in T3.1/T3.2.		
Collection Method	Partner metadata		
Validation / QA	QC by WP2		
Notes / Info Needed	Assign IDs consistently.		

Variable Name	data_update_frequency	Data Source	AIT / BMOB
Data Type	Numeric	Unit	Hz
Frequency	Continuous	Spatial Resolution	Site-level
		Linked Indicators	Data availability KPI
Definition / Description	Frequency of new data uploads from sensors or vehicles.		
Collection Method	Sensor logs / APIs / GPS devices		
Validation / QA	Compare vs expected rate		
Notes / Info Needed	Standardise by source type.		

Variable Name	data_accuracy_score	Data Source	AIT / LNEC
Data Type	Numeric	Unit	% accuracy
Frequency	Pilot cycle	Spatial Resolution	Site-level
		Linked Indicators	Data reliability KPI
Definition / Description	Reliability of data compared with ground truth.		
Collection Method	Cross-validation		

Validation / QA	Correlation analysis
Notes / Info Needed	Define accuracy threshold.

Variable Name	ground_truth_defects	Data Source	RoadLab / MoProVe
Data Type	Spatial	Unit	Count
Frequency	Periodic	Spatial Resolution	Road segment
		Linked Indicators	Calibration KPI
Definition / Description	Validated road defects for data calibration.		
Collection Method	Sensor-based		
Validation / QA	Comparison with imagery		
Notes / Info Needed	Confirm defect taxonomy.		

Variable Name	cost_per_km_data	Data Source	Partner finance logs
Data Type	Numeric	Unit	€/km
Frequency	Pilot	Spatial Resolution	Network-level
		Linked Indicators	CBA
Definition / Description	Cost of data acquisition per km monitored.		
Collection Method	Financial record		
Validation / QA	QA by finance partner		
Notes / Info Needed	Define cost components.		

Variable Name	vehicle_flow_per_day	Data Source	Road authority
Data Type	Numeric	Unit	Vehicles per day
Frequency	Pilot	Spatial Resolution	Site specific
		Linked Indicators	CBA
Definition / Description	Number of vehicles using a section of road on a daily basis		
Collection Method			
Validation / QA	QA		
Notes / Info Needed			

COMPONENT 3: DIGITAL TWINS

Variable Name	digital_connectivity_uptime	Data Source	System logs
Data Type	Numeric	Unit	%
Frequency	Continuous	Spatial Resolution	Network
		Linked Indicators	KPI 1: Connectivity performance, KPI 6: Sustainability and efficiency
Definition / Description	Percentage of time the digital twin infrastructure maintains an active and stable connection.		
Collection Method	API log monitoring		
Validation / QA	Automated uptime monitoring		
Notes / Info Needed	Threshold: uptime ≥ 95%.		

Variable Name	system_latency	Data Source	Network metrics
Data Type	Numeric	Unit	ms
Frequency	Continuous	Spatial Resolution	Network

		Linked Indicators	KPI 1: Connectivity performance, KPI 4: Decision support effectiveness
Definition / Description	Average data transfer time between sensors and twin.		
Collection Method	Log analysis		
Validation / QA	QC on outliers		
Notes / Info Needed	Confirm monitoring tool. Threshold for critical operations: < 5 second total delay		

Variable Name	data_refresh_rate	Data Source	Platform logs
Data Type	Numeric	Unit	Seconds/min
Frequency	Continuous	Spatial Resolution	System
		Linked Indicators	KPI 1: Connectivity performance, KPI 6: Sustainability and efficiency
Definition / Description	Frequency of sensor and operational data updates and made available within digital twin environment.		
Collection Method	System monitoring		
Validation / QA	Compare vs standard (platform standards and required update intervals)		
Notes / Info Needed	Establish baseline.		

Variable Name	visualisation_accuracy	Data Source	Ground validation data
Data Type	Numeric	Unit	% accuracy
Frequency	Per pilot	Spatial Resolution	Site
		Linked Indicators	KPI 2: Data accuracy and reliability, KPI5: Safety and asset improvements
Definition / Description	Degree to which displayed metrics (geometric, events (e.g. incidents) and pathologies (e.g. rutting)) match ground truth.		
Collection Method	Visual / analytical check		
Validation / QA	Field inspection; statistical accuracy validation (MAPE, RSME)		
Notes / Info Needed	Define tolerance band and accuracy threshold ($\geq 85\%$).		

Variable Name	user_interaction_frequency	Data Source	User logs
Data Type	Numeric	Unit	Count per month
Frequency	Monthly	Spatial Resolution	Pilot
		Linked Indicators	KPI 3: User adoption and uptake, KPI 4: Decision support system effectiveness KPI 5: Safety and asset improvements, KPI 6: Sustainability and efficiency
Definition / Description	Number of accesses, sessions and active users interacting with the digital twin tool.		
Collection Method	System usage stats (frequency of use, session duration, task completion rate)		
Validation / QA	Cross-check with user surveys and pilot team reporting		
Notes / Info Needed	Add user group breakdown (e.g. managers, operators, engineers, researchers). Target: 4/5 usability score		

Composite KPI datasets: some KPIs rely on combination of variables and external datasets. Composite dependencies are shown below.

Variable Names	user_interaction_frequency + data_refresh_rate + system_latency	Data Source	User logs+ Platform logs + Network metrics
----------------	---	-------------	--

Data Type	Numeric	Unit	Count / Seconds / Milliseconds
Frequency	Monthly / Continuous	Spatial Resolution	Pilot / System / Network
		Linked Indicators	KPI 4: Decision support effectiveness
Definition / Description	Quantifies the extent to which the digital twin enables faster decision-making and the number of decisions supported by digital twin insights.		
Collection Method	System usage stats / System monitoring / Log analysis / Decision event logs or insights		
Validation / QA	Cross-check usage with decision logs or insights (survey data): Collect pre-deployment decision making times from road managers or operation logs (baseline establishment). Compare baseline vs pilot pilot decision times.		
Notes / Info Needed	Target >15% reduction in response time compared to baseline. Minimum requirement is a demonstrated use of digital twin in at least one major decision category (e.g. incident response, maintenance prioritisation, ADAS validation) System performance must meet minimum thresholds (latency < 5s, stable data refresh)		

Variable Name	visualisation_accuracy + user_interaction_frequency	Data Source	Ground validation data + User logs
Data Type	Numeric	Unit	% accuracy / Count
Frequency	Per pilot	Spatial Resolution	Pilot
		Linked Indicators	KPI 5: Safety and asset performance improvements
Definition / Description	Captures how digital twin scenario-based insights improve risk mitigation and operational outcomes		
Collection Method	Visual - analytical check / System usage stats / scenario-specific safety and performance metrics		
Validation / QA	Confirm visualisation accuracy meets ≥ 85% threshold. Compare predicted risk reduction with actual or simulated outcomes (e.g. maintenance, incidents, ADAS events). Perform field inspection or simulation verification for scenario outcomes. Cross-check twin usage with interventions or scenario runs.		
Notes / Info Needed	Define tolerance ban per metric		

Variable Name	user_interaction_frequency + data_refresh_rate + digital_connectivity_uptime	Data Source	User logs+ Platform logs + System logs
Data Type	Numeric	Unit	Count / Seconds / %
Frequency	Monthly / Continuous	Spatial Resolution	Pilot / System / Network
		Linked Indicators	KPI 6: Sustainability and efficiency
Definition / Description	Measures operational cost and efficiency improvements enabled by the digital twin (across various scenarios, such as safety, maintenance, and ADAS scenarios)		
Collection Method	System usage stats / System monitoring / API log monitoring / Scenario-specific efficiency metrics (e.g. avoided test mileage, reduced interventions)		
Validation / QA	Cross-check usage with decision logs and scenario outputs. Validate reductions (e.g. in interventions, physical testing or travel time) against baselines. Ensure consistency of gains.		
Notes / Info Needed	Target: measurable reductions in operational time and costs.		

COMPONENT 4: ADAS PERFORMANCE

Variable Name	ADAS_performance_score	Data Source	Mobileye camera or in-vehicle camera
---------------	------------------------	-------------	--------------------------------------

Data Type	Categorical	Unit	%
Frequency	Scenario-based	Spatial Resolution	Route
		Linked Indicators	Safety KPI
Definition / Description	Measure of ADAS reliability under different conditions.		
Collection Method	CAN bus / logs		
Validation / QA	Scenario validation		
Notes / Info Needed	Calibration required.		

Variable Name	road_condition_index	Data Source	Inspection / ADAS data
Data Type	Numeric	Unit	Index
Frequency	Per pilot	Spatial Resolution	Section
		Linked Indicators	Asset-safety link
Definition / Description	Infrastructure quality influencing ADAS performance.		
Collection Method	Sensor / field		
Validation / QA	Cross-validation		
Notes / Info Needed	Define index scale.		

Variable Name	lane_detection_error_rate	Data Source	Mobileye camera or in-vehicle camera
Data Type	Categorical	Unit	% / count
Frequency	Continuous	Spatial Resolution	Segment
		Linked Indicators	System reliability
Definition / Description	Frequency of ADAS lane detection failures.		
Collection Method	CAN bus / logs		
Validation / QA	Comparison vs markings		
Notes / Info Needed	Define error threshold.		

Variable Name	ADAS_trigger_event_log	Data Source	Vehicle logs
Data Type	Categorical (state change signal)	Unit	Count
Frequency	Continuous	Spatial Resolution	Route
		Linked Indicators	Behavioural KPI
Definition / Description	Record of ADAS activations (e.g. driver switching on/off adaptive cruise control) and conflicts (e.g. a forward collision warning, automated emergency brake response).		
Collection Method	CAN data		
Validation / QA	Data parsing scripts		
Notes / Info Needed	Interpretation of a state change signal depends on the number of levels in the signal. E.g. an ADAS may have an 0/1 (on/off) signal, but it could also have multiple levels (if certain features are enabled). The number of levels and meaning of those levels may differ across vehicle types and manufacturers.		

Variable Name	maintenance_trigger_from_ADAS	Data Source	Pilot logs
Data Type	Numeric	Unit	Count
Frequency	Continuous	Spatial Resolution	Pilot
		Linked Indicators	Maintenance efficiency
Definition / Description	Instances where ADAS data informed maintenance.		
Collection Method	Workflow review		
Validation / QA	Verification by managers		
Notes / Info Needed	Confirm linkage process.		

COMPONENT 5: LOW-COST SAFETY INTERVENTIONS

Variable Name	intervention_id	Data Source	Pilot registry
Data Type	Text	Unit	ID
Frequency	Once	Spatial Resolution	Pilot
		Linked Indicators	CBA KPI
Definition / Description	Unique code for intervention tested. The codes will include reference to pilot location, and date reference.		
Collection Method	Manual		
Validation / QA	Quality control in project database		
Notes / Info Needed	Develop standard intervention code list.		

Variable Name	intervention_type_code	Data Source	Pilot inventory
Data Type	Text	Unit	Code
Frequency	Once	Spatial Resolution	Site
		Linked Indicators	Evaluation KPI
Definition / Description	Code for each type of intervention category (e.g. markings, crossing, signage).		
Collection Method	Manual coding		
Validation / QA	Partner review		
Notes / Info Needed	Typology finalisation needed.		

Variable Name	cost_per_intervention	Data Source	Pilot budgets
Data Type	Numeric	Unit	€
Frequency	Per intervention	Spatial Resolution	Site
		Linked Indicators	CBA KPI
Definition / Description	Total implementation cost. Service life, and maintenance cost.		
Collection Method	Financial records		
Validation / QA	QA by finance team		
Notes / Info Needed	Align cost elements. Workzone related travel time costs not included.		

Variable Name	safety_outcome_index	Data Source	iRAP data
Data Type	Numeric	Unit	%
Frequency	Before-after	Spatial Resolution	100 m
		Linked Indicators	Safety performance
Definition / Description	Change in safety risk (proxy, Star Rating, or FSI estimation).		
Collection Method	Model analysis using a baseline safety_risk_index and the after-implementation safety_risk_index		
Validation / QA	Quality control as part of WP6		
Notes / Info Needed	Define baseline.		

Variable Name	user_speed_profile	Data Source	Telematics / road loops
Data Type	Numeric	Unit	km/h
Frequency	Before-after	Spatial Resolution	Section or spot measurement(s)
		Linked Indicators	Behavioural KPI
Definition / Description	Speed change after intervention.		
Collection Method	Sensor / GPS / traffic counter		
Validation / QA	Outlier filtering		
Notes / Info Needed	Privacy & sampling info needed, in case of using app-based data.		

ANNEX 4: CBA METHODOLOGY REVIEW

The table below outlines the sources reviewed by partners as part of impact assessment planning (T2.4). The review identified a total of 53 sources and methodologies pertaining to CBA and wider impact assessment criteria for CAMBER solutions.

#	Source	Description	Source reference
1.	iRAP toolkit	Starting point for the list of road safety countermeasures and their potential impacts.	(iRAP, 2022)
2.	iRAP Safer Roads Investment Plans	Presents a framework for how to carry out CBA for different road safety treatments.	(iRAP, n.d.-c)
3.	European Road Safety Observatory (ERSO) CBA guide	Provides some guidance for principles and good practice for conducting a CBA for aspects such as calculating and analysing Net Present Value (NPV), Benefit Cost Ratio (BCR), among others.	(ERSO, 2018)
4.	A systematic cost-benefit analysis of 29 road safety measures	Presents CBA for a variety of measures using the SafetyCube methodology and demonstrates pertinent steps such as sensitivity analysis and considering various scenarios when conducting a CBA.	(Daniels et al., 2019)
5.	SAFESIDE: A computer-aided procedure for integrating benefits and costs in roadside safety intervention decision making	This study presents a computer aided procedure for performing a CBA of roadside safety interventions. It presents some guidance on aspects such as using Crash Prediction Models and combining effects of multiple measures.	(Roque & Cardoso, 2015)
6.	A novel methodology for planning urban road safety interventions	This research presents an integrated approach to road safety management combining reactive and predictive approaches using the iRAP star rating system and Geographic Information Systems (GIS).	(Toraldo et al., 2025)
7.	Data Envelopment Analysis for the assessment of road safety in urban road networks: A comparative study using CCR and BCC models	This research presents a Decision Envelopment Analysis (DEA). This approach is used to identify road locations that may need interventions to promote safety. The social cost of accidents is an output from the methods defined.	(Fancello et al., 2020)
8.	An analysis of official road crash cost estimates in European countries	This research utilises the SafetyCube methodology to provide crash cost calculations (2015) and how they differ in 31 European countries.	(Wijnen et al., 2019)
9.	SafetyCube – Guidelines for Priority Setting Between Measures with Practical Examples	This study utilises the SafetyCube DSS methodology that provides evidence on crash reduction for a variety of countermeasures dating from 2017. It also offers a useful categorisation of countermeasures into four groups	(Martensen et al., 2018)

#	Source	Description	Source reference
		representing risk patterns in a simple manner.	
10.	Deriving a joint risk estimate from dynamic data collected at motorcycle rides	This study presents a methodology where hazardous spots were predicted for motorcyclists using vehicle dynamics data. This can be relevant to CAMBER for identifying priority treatment sites for pilot sites.	(Hula et al., 2021)
11.	A methodology to assess pedestrian crossing safety	This study represents a methodology for assessing the safety of a pedestrian crossing in urban areas. A comprehensive index for pedestrian crossing safety has been developed as part of this project.	(Basile et al., 2010)
12.	Safety Assessment for Design and Redesign of Horizontal Curves	This study utilises the Dangerous Curves Detection System (PERVEL) methodology, a method for detecting dangerous curves on rural roads. Accident rates were predicted on curves and tangents using log-linear models.	(Cardoso, 2005)
13.	Comparative safety analysis of a two-lane two-way highway, using IHSDM and a Portuguese procedure	The study relates to the application of PERVEL and the Interactive Highway Safety Design Manual (IHSDM). Currently, the IHSDM software comprises of aspects pertaining to evaluating the safety and operational performance of two-lane rural highways design. Some of these aspects can be relevant to CAMBER such as analysing the impact of the geometric design.	(Cardoso et al., 2010)
14.	Infrastructure Risk Rating Manual	Infrastructure Risk Rating (IRR) is a method for assessing road safety risk similar to iRAP star ratings but requires fewer inputs. IRR uses eight key attributes of roads and roadsides to produce a risk score.	(NZTA, 2024)
15.	Quantification of road safety risk at locations without collisions to justify road safety investments	This study calculates a road safety risk index that gives a proactive measure of risk along with a Proactive Funding Index (PFI). The approach is relevant for understanding risks at high crash locations. PFI helps identify the recommended funding level for a project.	(de Leur & Hill, 2015)
16.	Safe Cycling Network	This report forms the basis for the CycleRAP methodology to assess the safety of cycling infrastructure. The methodology assesses 25 safety features based on 360° pictures of sections (per 25m).	(Wijlhuizen et al., 2014)
17.	Network Wide Road Safety Assessment	This report pertains to a handbook that outlines guidance on conducting a network wide road safety assessment. The handbook outlines some proactive	(National Technical University of

#	Source	Description	Source reference
		and reactive safety measures and assessments.	Athens et al., 2023)
18.	European Common Evaluation Methodology for CCAM	The handbook clearly highlights some principles, benefits and challenges for conducting a CBA for CCAM methodologies. It also helps in identifying some surrogate measures for data sources related to CCAM.	(FAME, 2025)
19.	Trilateral Impact Assessment Framework for Automation in Road Transportation	This study discusses an automation impact assessment framework largely suited for Field Operational Tests (FOTs). It considers some first and second order impacts such as safety, efficiency, congestion, among others.	(Innamaa et al., 2018)
20.	FESTA Methodology	The FESTA methodology presents a pre-cursor to the European Common Evaluation Methodology. It provides guidance on identifying real-world effects and benefits for Field Operational Tests (FOTs) and Naturalistic Driving Studies (NDS).	(FOT-NET, 2011)
21.	iRAP star rating methodology	The iRAP Start ratings and FSI estimations can be used to measure the road safety impact	(iRAP, n.d.-b)
22.	iRAP Crash Risk Mapping	iRAP crash risk maps use detailed crash data to capture the risk arising from the interaction of road users, vehicles and the road environment. Crash risk mapping could be used to help identify some potential locations where there could be risky locations for the CAMBER pilot sites.	(iRAP, n.d.-a)
23.	European V4Safety project (The V4Safety CBA tool)	It allows to calculate the costs and benefits of vehicle safety systems (ADAS) and help to spend resources efficiently and prevent more road casualties within the financial restrictions. This methodology is relevant to CAMBER to identify cost-effective measures to address the risks of fatal and serious crashes on urban and secondary roads.	(Wijnen, 2025)
24.	On the road safety benefits of advanced driver assistance systems in different driving contexts	It integrates the literature on advanced driving technologies and road safety to quantify the expected impact of ADAS on accident reduction. It aligns closely with CAMBER Task 2.3 by showing how environmental factors affect ADAS performance. Its Analytic Hierarchy Process (AHP) framework supports multi-criteria decision-making for safety interventions, while its use of accident data helps identify high-impact technologies and pilot sites. It offers a	(Masello et al., 2022)

#	Source	Description	Source reference
		practical model for integrating safety into asset management.	
25.	Monetary and Prospective Benefit Assessment Method for Advanced Driver Assistance Systems	The study looked at quantifying the economic benefit of ADAS technologies, primarily focusing on low-speed systems such as Autonomous Emergency Braking (AEB)). While the study did not express benefits in explicit currency values, percentages were provided for some estimation of impact.	(Feig et al., 2017)
26.	PIARC Road Safety Manual	This is a comprehensive resource that provides some practical steps for conducting an impact assessment. It provides guidance on important steps to be conducted in a CBA such as valuing costs, monetary values for crash reduction, among others.	(PIARC, 2024)
27.	Study on the Deployment of C-ITS in Europe	This study demonstrates a economic assessment of deploying C-ITS in Europe. It quantifies safety, efficiency, and environmental benefits and compares them with the deployment/operating costs. The research found that that there is a significant benefit from investing in these resources and technologies.	(Asselin-Miller et al., 2016)
28.	C-Mobile	Ex-ante CBA for bundled C-ITS services was conducted. BCRs were calculated for chosen target years with a detailed description of costs and benefits for these services.	(Mitsakis et al., 2018)
29.	L3 Pilot Driving Automation	L3 Pilot is a real-world pilot in Europe to assess Automated Driving Functions (ADF). A socio-economic assessment was also performed to evaluate the benefits of ADF. A similar approach to the impact assessment can be followed for the CBA analysis.	(Bjorvatn et al., 2021; Metz et al., 2019)
30.	C-Roads Platform, Evaluation and Assessment Plan (WG3), EU deployment platform	This study pertains to harmonised socio-economic assessment guidelines for C-ITS pilots inclusive of KPIs and data. This can be potentially used to plan templates for CAMBER's datasets, KPIs and evaluation pipelines for connected services.	(Studer et al., 2023)
31.	Guide to Cost-Benefit Analysis of Investment Projects	This report from the European Commission provides a structured EU-approved framework to assess the economic impact of connected maintenance and safety services/	(Sartori et al., 2014)
32.	A Cost-Benefit Approach for Analysing the Impact of eCall Technology on the EU Passenger Vehicles	This report focuses on applying a CBA analysis to eCall technology. Researchers setup a framework for performing a CBA and quantified lives	(Zirra et al., 2022)

#	Source	Description	Source reference
		via faster response times. This can be applied in CCAM/ADAS contexts where a faster hazard response can be seen as monetised safety benefits in these contexts.	
33.	Economic Appraisal Vademecum 2021 - 2027	This guide sets out some of the principles for a CBA analysis and applications of the analysis that can be used across EU projects.	(Sartori et al., 2021)
34.	Cost-Benefit Analysis of Construction Information Management System Implementation	This study presents a practical application of a CBA analysis or construction projects. It proposes a CBA framework in this context and determines the costs and benefits involved.	(Vaughan et al., 2013)
35.	The Impact of Data Integration on the Costs and Benefits of Information Systems	This study presents a theoretical framework for conducting an impact assessment. It considers partial and full data integration scenarios. If the integration creates a net value or excessive integration, it generates unnecessary costs. It also presents a framework for modelling marginal benefits and costs of data fusion.	(Goodhue et al., 1992)
36.	The Cost of Activity-Based Management	It supports inclusion of change management, training, data quality assurance, and governance overheads in CBA inputs, and it encourages sensitivity testing on these “hidden” cost categories. Overall, it recommends including organisational or change management costs to avoid inflating the CBA analysis.	(Armstrong, 2002)
37.	Economics of Digital Twins	This study represents a comprehensive review of the impact assessment of Digital Twins. It examines the costs and benefits for DTs along with areas where DTs will be the cost effective. This can be useful for CAMBER’s DT component.	(Thomas, 2024)
38.	Evaluating the Economic Impact of Digital Twinning in the AEC Industry: A Systematic Review	This research conducts an impact assessment for DT specifically in the context of the Architecture, Engineering, and Construction (AEC) industry using the PRISMA methodology. The study included quantified case-based cost efficiencies from construction projects using DTs.	(Karunaratne et al., 2025)
39.	Digital Twin Enabling Technologies for Advancing Road Engineering and Lifecycle Applications	This DT study presents a lifecycle-based justification for prioritising DT benefits in operations and maintenance phases, where cost savings are most tangible. In CAMBER, it can support linking DT benefits to reduced inspection and maintenance costs, enabling sensitivity	(Yan et al., 2025)

#	Source	Description	Source reference
		testing for road asset management aspects such as defect detection, among others.	
40.	Integrated Network Management Digital Twin: Economic Benefits Analysis	This is a study based in the UK where the Department of Transport aims to quantify the benefits of a digital twin. It uses a CBA methodology aligned with UK TAG guidance that is equivalent to the EU CBA standards. The purpose of this study was to demonstrate how digital twins generate monetisable values in the transport domain.	(Department for Transport & Arup, 2024)
41.	Retrofitting ADAS for Enhanced Truck Safety: Analysis Through Systematic Review, Cost-Benefit Assessment, and Pilot Field Testing	A CBA analysis was conducted for trucks particularly in the Italian context using the SafetyCube DSS methodology. This research particularly relates to ADAS for trucks. A cost-effectiveness analysis of retrofitting ADAS on actual trucks was employed as part of this study.	(Pizzicori et al., 2025)
42.	Evaluation framework for domain-specific digital twin platforms	This study provides a comprehensive evaluation for DT platforms with a focus on Domain-Specific applications. The framework uses the Best-Worst Method and Fuzzy Comprehensive Evaluation (BWM-FCE). This could be applicable as part of the wider impact evaluation as part of CAMBER.	(Tang et al., 2025)
43.	Digital Twin Maturity Model	This study focuses on a Digital Twin Maturity Model (DT MM) to assess DTs. A maturity index was developed to assess the overall maturity of DTs. Some of the evaluation factors include computing capabilities, integration, HMI, among others.	(Uhlenkamp et al., 2022)
44.	A Data Integration Platform for patient-centered e-healthcare and clinical decision support	This research focuses on evaluating an open data integration platform intended for patient centred e-healthcare. Researchers used IS participation theory (Markus and Mao's theory) linking stakeholder involvement and participation (patients, providers, carers, external entities) to overall system success. Researchers designed some success metrics and other core functionality metrics for evaluating the data platform.	(Jayaratne et al., 2019)
45.	Assessing the impact of automation in pharmaceutical quality control labs using a digital twin	This study uses a DT as an evaluation tool. Various scenarios are run within the DT and the effects are measured on aspects such as productivity, labour requirements, efficiency, among others. Here, the DT itself acts as the	(Coito et al., 2022)

#	Source	Description	Source reference
		environments for quantitative “what-if” evaluations.	
46.	An integrative evaluation framework for intelligent decision support systems	This study proposes a structured, multi-criteria framework for evaluating intelligent decision-support systems (IDSS). These systems combine data, models and AI techniques. The outlined framework in this study can be adapted to assess how well maintenance and safety information is integrated to support prioritisation and decision-making in CAMBER.	(Phillips-Wren et al., 2009)
47.	Integrated Decision-Making Framework in Industrial Asset Management for Assessing and Managing Emerging Risks	This study combined two frameworks – Functional Resonance Analysis Method (FRAM) and System Theoretic Accident Model and Processes (STAMP) to assess system dependencies and safety constraints. This approach has been designed in the context of industrial asset management and demonstrates how automation systems and human-system interactions can be assessed for safety and reliance.	(Diop et al., 2024)
48.	A Systematic Review of Asset Integrity and Process Safety Management Sustainability for Onshore Petrochemical Installations	This study proposes an Integrated Asset Integrity and Process Safety Management (iAIPSM) framework that combines asset integrity management and process safety management. iAIPSM contains 17 elements with organisations using these to spot inconsistencies. It also introduces a four-phase maturity model to guide implementation and continuous improvement.	(Ayomoh & Ongwae, 2025)
49.	A comprehensive review of the socio-economic appraisal methodologies of the road safety measures	This research paper gives a comprehensive overview of some of the principles of CBA and offers some guidance on CBA approaches based on the type of evidence available. It offers a detailed review of the types of resources and explores various CBA indicators while considering the quality of the datasets and in which context have they been used.	(Putatunda et al., 2025)
50.	Valuing the wider benefits of road maintenance funding	This study refers to a model to evaluate the benefits of highway maintenance spending on local roads in England. The research tries to capture the wider benefits such as reduced vehicle operating costs, time savings, among others.	(Thiessen et al., 2017)
51.	The impact of indirect benefits (reduced travel time, fuel use and	This study aims to focus on the indirect effects associated with economic evaluations. The impact of indirect	(Byaruhanga & Evdorides, 2024)

#	Source	Description	Source reference
	emissions) in cost benefit analysis of road safety countermeasures	benefits was demonstrated with a quantitative study for an infrastructure improvement programme in the Netherlands.	
52.	Cost-benefit analysis of innovative automative safety systems	This study discusses the methodology for conducting CBA particularly for vehicle safety systems. The research also involves a CBA tool that can be utilised for this purpose. However, it requires inputs from users related to crash costs and benefits.	(Bützer et al., 2022)
53.	Impact analysis of Advanced Driver Assistance Systems (ADAS) regarding road safety – computing reduction potentials	This paper evaluates how nine selected ADAS technologies could reduce road crashes and fatalities using Austrian crash data by 2025, 2030 and 2040. It quantifies the safety impact using national crash data.	(Aleksa et al., 2024)

ANNEX 5: PILOT SITE APPLICATION PER COMPONENT

The tables in this annex details *preliminary plans* for demonstrations in each pilot site, presented separately per CAMBER project component. Activity codes are found in Table 4 in Section 5.1.2 of the main document. The following prefixes are used for these activity codes: TRIK = Trikala, CROA = Croatia, CASC = Cascais, SPAI = Spain, NHOL = North Holland.

COMPONENT 1: SAFETY-INTEGRATED MAINTENANCE SYSTEMS AND PROCESSES

Activity code	Preliminary plans for pilot demonstration
TRIK1	Crowdsourced Pavement Intelligence ICCS: intelligence & platform dev; ETRIK: API to TMC & georeferenced photos; IRAP: road conditions framework
CROA1 CROA3	Application of coloured pavement (anti-slip surfaces) at horizontal curve and in front of pedestrian crossing and additional signage at pedestrian crossing on state road DC43
CROA2	Application of modified optical transverse markings on a curved road section and in front of a pedestrian crossing on state road DC48.
CROA1	The use of impact sensors on guardrails
CASC1 CASC3	Detection of dangerous sites per road user type: mapping high frequency crowdsourced (PVD & MOBILEYE) sudden manoeuvres (AGIL, LNEC)
CASC1	Correlation between standardized indexes (e.g. road surface characteristics) and PVD generated indicators
CASC1 CASC2 CASC3	Mapping/Rating of availability of infrastructure-based support to ADAS (e.g. ISA and lane keeping) (PVD & MOBILEYE)
CASC2	Estimation of AADT, based on traffic counts and crowdsourced data (PVD)
SPAI1	Shoulder Condition Assessment and Maintenance: Determine the geometric and effective shoulder width, characterize conditions, and identify elements unsuitable for cyclists. Evaluate road conditions using collected GT data as part of the safety-integrated maintenance system. Perform interventions and reevaluate using CycleRAP/Star Rating.
SPAI2	Superelevation Measurement for Maintenance Prioritization: Evaluate the feasibility, accuracy, and performance of superelevation (banking) measurement in curved segments using GT data (IMU/LiDAR).

Activity code	Preliminary plans for pilot demonstration
NHOL1	Mapping and assessment of existing asset and safety data, CycleRAP / iRAP Star Ratings, ROMO vehicle sensor data, Flitsmeister reports, and Roadlab/MoProVe scans SWOV (pilot lead, analysis), Province of North Holland (data, maintenance workflow integration), iRAP (CycleRAP/Star Ratings), AIT (Roadlab/MoProVe ground-truth scans), AGIL (data fusion where relevant)
NHOL2	Identification of cycle track deficiencies (surface, debris, marking visibility, lighting) and unsafe cyclist crossings on higher-speed roads via ROMO probe data, Flitsmeister reports, Roadlab scans, and CycleRAP scoring. Prioritise low-cost interventions and evaluate before/after safety effects. SWOV (risk analysis & CycleRAP), Province of North Holland (intervention decisions & maintenance), AIT (ProMoVo / Roadlab data), iRAP (VRU risk evaluation), BMOB (crowdsourced hazard reports)**

COMPONENT 2: NEW-GENERATION DATA SOURCES

Activity code	Preliminary plans for pilot demonstration
TRIK1	Crowdsourced Pavement Intelligence ICCS: intelligence & platform dev; ETRIK: API to TMC & georeferenced photos; IRAP: road conditions framework
TRIK2	Urban-Secondary Road Inventory AIT: RoadLab, data collection, analysis, visualisation; VIC: GIS system; IRAP: road conditions framework; ICCS/ETRIK: API, logistics
CROA1	The use of impact sensors on guardrails Detection of dangerous sites: mapping testing-survey vehicle indicators (AIT-MoProVe)
CASC1 CASC3	Detection of dangerous sites per road user type: mapping high frequency crowdsourced (PVD & MOBILEYE) sudden manoeuvres (AGIL, LNEC)
CASC1 CASC2	Detection of dangerous sites: mapping testing-survey vehicle indicators (AIT-motorcycle)
CASC1 CASC2 CASC3	Correlation between high crash frequency/risk sites and crowdsourced detected sites and AIT ratings
CASC1	Correlation between standardized indexes (e.g. road surface characteristics) and PVD generated indicators

Activity code	Preliminary plans for pilot demonstration
CASC2	Detection of pavement deterioration by means of InSAR data or crowdsourced data (PVD)
CASC1 CASC2 CASC3	Mapping/Rating of availability of infrastructure-based support to ADAS (e.g. ISA and lane keeping) (PVD & MOBILEYE)
CASC1	Correlation between optical characteristics and readability of traffic signs and markings (PVD & MOBILEYE)
SPA11	High-Resolution Data for Cyclist Infrastructure Assessment: Utilize Image and LiDAR technologies to collect GT data to determine geometric and effective shoulder width and characterize conditions (e.g. potholes, debris, vegetation).
SPA12	IMU and LiDAR Data for Road Geometry: Analyze viability and precision of obtaining transverse superelevation on curves using IMU data and generating cross-sections from a LiDAR point cloud Digital twin.
SPA13	Dynamic and Crowdsourced Data Integration: Integrate and explore dynamic data (e.g. harsh events) for enhancing road evaluation and use cyclist activity data to drive the Digital Twin decision-support component.
NHOL1	Mapping and assessment of existing asset and safety data, CycleRAP / iRAP Star Ratings, ROMO vehicle sensor data, Flitsmeister reports, and Roadlab/MoProVe scans SWOV (pilot lead, analysis), Province of North Holland (data, maintenance workflow integration), iRAP (CycleRAP/Star Ratings), AIT (Roadlab/MoProVe ground-truth scans), AGIL (data fusion where relevant)
NHOL2	Identification of cycle track deficiencies (surface, debris, marking visibility, lighting) and unsafe cyclist crossings on higher-speed roads via ROMO probe data, Flitsmeister reports, Roadlab scans, and CycleRAP scoring. Prioritise low-cost interventions and evaluate before/after safety effects. SWOV (risk analysis & CycleRAP), Province of North Holland (intervention decisions & maintenance), AIT (MoProVe / Roadlab data), iRAP (VRU risk evaluation), BMOB (crowdsourced hazard reports)**
NHOL3	Identification of high-risk curves using ROMO driver behaviour signals (e.g. steering corrections, near-misses), probe vehicle IMU data, and existing crash records. Implement and evaluate hazard warnings and advisory speeds delivered through Flitsmeister and assess safety impact using behavioural metrics. BMOB (hazard messaging & driver behaviour data), SWOV (analysis & hotspot identification), Province of North Holland (policy & signposting decisions), AGIL (data environment integration)

Activity code	Preliminary plans for pilot demonstration
NHOL4	<p>Trial of real-time hazard warnings for drivers near school zones using IoT-triggered alerts (e.g. crossing guard stop-sign signal → in-vehicle message via Flitsmeister). Monitoring of behavioural response and evaluate feasibility of scalable deployment.</p> <p>BMOB (Flitsmeister real-time alerts), SWOV (impact evaluation), Province of North Holland (local implementation with schools/municipalities).</p>

COMPONENT 3: DIGITAL TWINS

Activity code	Preliminary plans for pilot demonstration
TRIK2	<p>Urban-Secondary Road Inventory</p> <p>AIT: RoadLab, data collection, analysis, visualisation; VIC: GIS system; IRAP: road conditions framework; ICCS/ETRIK: API, logistics</p>
TRIK2	<p>DT-Based Road Simulation and Validation</p> <p>AIT: DT; VIC: GIS system; ICCS: simulation/scenarios; ETRIK: scenarios / interventions realization</p>
CROA1	Detection of dangerous sites: mapping testing-survey vehicle indicators (AIT-MoProVe)
CROA1	Detection of dangerous sites: mapping testing-survey vehicle indicators (AIT-Roadlab)
CASC1 CASC3	Detection of dangerous sites per road user type: mapping high frequency crowdsourced (PVD & MOBILEYE) sudden manoeuvres (AGIL, LNEC)
CASC1 CASC2	Detection of dangerous sites: mapping testing-survey vehicle indicators (AIT-motorcycle)
CASC2	Estimation of AADT, based on traffic counts and crowdsourced data (PVD)
SPA1	GT Data Integration and Quality Assessment: Collect high-resolution GT data or the Digital Twin (GIS) to assess the quality of digitalized information and identify dangerous sites for cyclists.
SPA2	Geometry Modelling and Inventory: Use LiDAR data to generate transverse profiles from point cloud models for accurate road geometry assessment (superelevation). This contributes to the road asset inventory within the Digital Twin.

SPA13	Decision-Making and Intervention Simulation: Implement a DT component to support decision-making for urban traffic management, including the planning and evaluation of low-cost engineering interventions.
NHOL1	Mapping and assessment of existing asset and safety data, CycleRAP / iRAP Star Ratings, ROMO vehicle sensor data, Flitsmeister reports, and Roadlab/MoProVe scans SWOV (pilot lead, analysis), Province of North Holland (data, maintenance workflow integration), iRAP (CycleRAP/Star Ratings), AIT (Roadlab/MoProVe ground-truth scans), AGIL (data fusion where relevant)
NHOL2	Identification of cycle track deficiencies (surface, debris, marking visibility, lighting) and unsafe cyclist crossings on higher-speed roads via ROMO probe data, Flitsmeister reports, Roadlab scans, and CycleRAP scoring. Prioritise low-cost interventions and evaluate before/after safety effects. SWOV (risk analysis & CycleRAP), Province of North Holland (intervention decisions & maintenance), AIT (ProMoVo / Roadlab data), iRAP (VRU risk evaluation), BMOB (crowdsourced hazard reports)**

COMPONENT 4: ADAS PERFORMANCE

Activity code	Preliminary plans for pilot demonstration
TRIK2	DT-Based Road Simulation and Validation AIT: DT; VIC: GIS system; ICCS: simulation/scenarios; ETRIK: scenarios / interventions realization
CROA3	Determining the impact of traffic signalling quality on the ADAS system; devices for measuring the quality of traffic signs and road markings and Mobileye readings.
CASC1 CASC2 CASC3	Mapping/Rating of availability of infrastructure-based support to ADAS (e.g. ISA and lane keeping) (PVD & MOBILEYE)
NHOL3	Identification of high-risk curves using ROMO driver behaviour signals (e.g. steering corrections, near-misses), probe vehicle IMU data, and existing crash records. Implement and evaluate hazard warnings and advisory speeds delivered through Flitsmeister and assess safety impact using behavioural metrics. BMOB (hazard messaging & driver behaviour data), SWOV (analysis & hotspot identification), Province of North Holland (policy & signposting decisions), AGIL (data environment integration)
NHOL4	Trial of real-time hazard warnings for drivers near school zones using IoT-triggered alerts (e.g. crossing guard stop-sign signal → in-vehicle message via

	<p>Flitsmeister). Monitoring of behavioural response and evaluate feasibility of scalable deployment.</p> <p>BMOB (Flitsmeister real-time alerts), SWOV (impact evaluation), Province of North Holland (local implementation with schools/municipalities).</p>
--	--

COMPONENT 5: LOW-COST SAFETY INTERVENTIONS

Activity code	Preliminary plans for pilot demonstration
TRIK1	<p>Relevant interventions include (subject to decision if piloted, based on WP4 results and budget availability):</p> <p>Coloured surfacing (e.g. red asphalt in conflict zones or cycling paths)</p> <p>Cycle lanes with visual separation (paint or colour) → <i>already there; TBC if valuable for selected segment(s)</i></p> <p>In-ground lighting for pedestrian crossing</p> <p>Zebra crossings with advance yield markings</p>
TRIK2	<p>Relevant interventions include (subject to decision if piloted, will be based on WP4 results and budget availability):</p> <p>Improved sign placement and visibility (i.e. retroreflective pavement markings and signing during nighttime)</p> <p>Alternating road markings (e.g. dragon teeth, coloured markings)</p> <p>Advance warning signs for curves, intersections, or schools</p> <p>Unsignalised crossing in front of a school zone (camera detects VRU - sends message to lower speed)</p>
CROA1 CROA3	<p>Application of coloured pavement (anti-slip surfaces) at horizontal curve and in front of pedestrian crossing and additional signage at pedestrian crossing on state road DC43</p>
CROA2	<p>Application of modified optical transverse markings on a curved road section and in front of a pedestrian crossing on state road DC48.</p>
CASC1	<p>Testing new solutions to elicit driving behaviour using harsh events – MOBILEYE (e.g. approach to roadwork zones, pedestrian crossings, PTW on bends)</p>
SPA11	<p>Targeted Intervention Identification and Evaluation: Safety evaluation (CycleRAP/iRAP Star Rating) identifies unsuitable elements (e.g. potholes, debris) for cyclists. Perform interventions based on shoulder assessment and reevaluate.</p>
SPA13	<p>Intervention Implementation and Impact Assessment: Perform and evaluate to-be-determined low-cost engineering interventions (e.g. paintings, barriers) with a before-and-after comparison using iRAP Star Rating and/or CycleRAP</p>

	assessment tools. This includes the dynamic speed adjustment (via warnings) as an operational intervention.
NHOL1	<p>Mapping and assessment of existing asset and safety data, CycleRAP / iRAP Star Ratings, ROMO vehicle sensor data, Flitsmeister reports, and Roadlab/MoProVe scans</p> <p>SWOV (pilot lead, analysis), Province of North Holland (data, maintenance workflow integration), iRAP (CycleRAP/Star Ratings), AIT (Roadlab/MoProVe ground-truth scans), AGIL (data fusion where relevant)</p>
NHOL2	<p>Identification of cycle track deficiencies (surface, debris, marking visibility, lighting) and unsafe cyclist crossings on higher-speed roads via ROMO probe data, Flitsmeister reports, Roadlab scans, and CycleRAP scoring. Prioritise low-cost interventions and evaluate before/after safety effects.</p> <p>SWOV (risk analysis & CycleRAP), Province of North Holland (intervention decisions & maintenance), AIT (ProMoVo / Roadlab data), iRAP (VRU risk evaluation), BMOB (crowdsourced hazard reports)</p>
NHOL3	<p>Identification of high-risk curves using ROMO driver behaviour signals (e.g. steering corrections, near-misses), probe vehicle IMU data, and existing crash records. Implement and evaluate hazard warnings and advisory speeds delivered through Flitsmeister, and assess safety impact using behavioural metrics.</p> <p>BMOB (hazard messaging & driver behaviour data), SWOV (analysis & hotspot identification), Province of North Holland (policy & signposting decisions), AGIL (data environment integration)</p>