NATIONAL UNIVERSITY OF LIFE AND ENVIRONMENTAL SCIENCES OF UKRAINE

THE ACADEMY OF APPLIED SCIENCE
ACADEMY OF MANAGEMENT AND ADMINISTRATION IN OPOLE

CARGO INTEGRITY IN ROAD LOGISTICS

MONOGRAPH



OPOLE-KYIV 2026

Academy of Applied Sciences
Academy of Management and Administration in Opole
National University of Life and
Environmental Sciences of Ukraine

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CARGO INTEGRITI IN ROAD LOGISTICS

Monograph

Opole-Kyiv
2026

ISBN 978-83-66567-74-0

Cargo Integriti in Road Logistics. Monograph. Opole: Academy of Applied Sciences Academy of Management and Administration in Opole, 2026;
ISBN 978-83-66567-74-0; 206 pp., illus., tabs., bibls.

Together with:
National University of Life and Environmental Sciences of Ukraine, Kyiv

Recommended for publication
by the Academic Council of Academy of Applied Sciences
Academy of Management and Administration in Opole
(Protocol No. 12 of November 06, 2026)

Editorial Office:
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Academy of Management and Administration in Opole
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Publishing House:
Academy of Applied Sciences Academy
of Management and Administration in Opole,
45-085 Poland, Opole, ul. Niedzialkowskiego 18
tel. 77 402-19-00/01

150 copies

Authors are responsible for content of the materials
ISBN 978-83-66567-74-0
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INTRODUCTION

The efficient functioning of logistics supply chains, covering all stages of material flows – from the supply of raw materials and semi-finished products to the delivery of finished products to the end consumer, as well as the organization of reverse logistics flows, is one of the key factors in ensuring the sustainability and competitiveness of enterprises in the modern economy. In the context of large-scale cataclysms (wars, pandemics), high volatility of the market environment, increased uncertainty and risks, tightening requirements for the quality of logistics services, the issues of reliability of transport operations and the safety of cargo movement are of particular importance.

The transport component of the logistics chain significantly affects both the overall level of logistics costs and the quality of customer service. At the same time, transportation costs are formed not only due to the direct performance of transportation, but also include costs associated with violation of delivery deadlines, downtime of vehicles, additional transshipment operations, as well as losses from damage, damage or complete loss of cargo. A significant share in this structure is occupied by the costs caused by the implementation of transport risks, in particular the risks of non-safety of goods.

Road transport occupies a leading place in freight transportation due to its versatility, mobility and the ability to provide door-to-door delivery. At the same time, road transportation is characterized by increased sensitivity to the impact of a wide range of risk-forming factors (technical, organizational, technological, human and related to the influence of the external environment). This leads to a fairly high prevalence of cases of non-safety of goods in the process of transportation, which negatively affects the economic results of carriers' activities, the level of customer satisfaction and the efficiency of logistics systems in general.

Cargo safety is one of the basic characteristics of the quality of transport services and the main contractual responsibility of the carrier. Non-safety of goods belongs to the transport risks of a man-made nature and manifests itself in the form of mechanical damage, deformation, damage, loss of commercial properties or complete loss of cargo. The formation of such risks has a complex multifactorial nature and is the result of the interaction of transportation conditions, cargo characteristics, technical condition of vehicles, quality of packaging and fastening, the level of organization of the transport process and personnel actions.

Despite the application in practice of a wide range of organizational and technical measures to ensure the safety of goods – the use of specialized rolling stock, modern means of fastening, traffic monitoring and control systems, improvement of transportation routes – the level of non-safety remains significant. This indicates the limitations of fragmented measures and the need to move to systematic risk management based on quantitative assessment, modeling and forecasting.

The analysis of scientific research in this area shows that most of the works are devoted to certain aspects of the problem: the study of the causes of damage to specific types of cargo, the analysis of technical solutions or regulatory requirements for transportation. At the same time, the issues of formalization of the process of formation of risks of non-safety of goods, determination of their structure, hierarchy and interconnections, as well as the construction of integrated risk indicators suitable for use in the practice of logistics process management remain insufficiently developed.

In this regard, the development of a methodological approach to assessing the risks of non-safety of goods, which is based on:

– systematic analysis of risk factors, taking into account their internal and external nature;

– application of methods of multi-criteria assessment and decision-making theory;

– the use of mathematical modeling to quantify the level of risk;

– formation of integrated risk indices as a tool to support management decisions.

It is this approach that allows us to move from a descriptive analysis of individual cases of non-safety of goods to a comprehensive risk assessment at the level of the logistics chain and the transport process as a whole. This creates the basis for an informed choice of risk mitigation measures, optimization of technological solutions and increase the reliability of road transportation.

In this context, this monograph is aimed at forming a holistic system of methods and models for assessing the risks of non-safety of goods in the process of road transportation. The logic of presenting the material provides for a consistent transition from the identification and classification of risk factors to the development of quantitative methods for their assessment, the construction of mathematical models and integrated risk indicators, as well as the formation of practical recommendations for managing the risks of cargo non-safety in modern logistics systems.

CHAPTER 1

REGULATORY AND LEGAL FRAMEWORK FOR CARGO SECURING SAFETY AND CARGO INTEGRITY IN ROAD TRANSPORT

1.1. Safety of road freight transport in Europe: an overview

EU road safety policy rests on a long-term target set in the 2011 Transport White Paper: by 2050, the number of road deaths in the Union should approach zero [17]. This goal is known as Vision Zero. For the freight segment, it means a shift from investigating the causes of accidents after they have happened to removing the conditions under which an accident becomes possible. Cargo securing is one of these conditions. Unlike speed or driver fatigue, its state can be checked before departure and corrected if necessary.

Preliminary data from the European Commission show that about 20 600 people were killed on EU roads in 2022. This is 3 % more than in 2021, when traffic had not yet recovered from pandemic restrictions, but about 10 % fewer than in 2019 [19]. The long-term trend thus remains downward, although the rate of decline is insufficient to reach the interim targets.

The share of freight transport in these statistics is described in the analytical materials of the European Road Safety Observatory (ERSO). In 2020, 2 496 people were killed in EU road crashes involving heavy goods vehicles (HGVs), or about 14 % of all road deaths [20]. The breakdown of these fatalities is revealing. On average over 2018–2020, only 12 % were drivers and passengers of the trucks themselves; the rest were other road users, including 29 % pedestrians, cyclists and riders of powered two-wheelers [20]. The danger posed by freight transport is thus largely borne by people who have no influence over how the cargo is loaded and secured. For this reason, cargo securing requirements in the EU are a matter of public law enforced by the state, even though they could in principle have remained a matter of agreement between carrier and cargo owner.

Road freight transport in the EU amounted to about 1 920 billion tonne-kilometres in 2022, the same level as in 2021 [22]. Heavy flows of HGVs on international corridors raise the requirements for the technical condition of the fleet, for the organisation of drivers' working time and for cargo securing. Securing violations differ from other violations in that they are difficult to see from outside. A curtain conceals how the cargo is placed. Lashings may be tensioned but attached at an unfavourable angle. The nominal capacity of a lashing may not match its actual condition after several hundred cycles of use.

Analysis of individual cargo shifting incidents confirms that their causes are usually complex. A. Nieoczym, J. Caban and J. Vrabel examined a case of improperly secured cargo and showed how errors in choosing the securing

method and in estimating friction forces lead to loss of cargo stability while driving [52]. A broader overview of cargo loss risks in road transport is given in the systematic review by P. Panjee and co-authors. The authors grouped the risks into technical, human, organisational and external factors and pointed to the lack of integrated approaches to assessing them [56].

Three conclusions are important for what follows. Road freight transport accounts for a notable share of fatal road crashes in Europe, and most of those killed are other road users. Cargo securing is among the factors that can be managed before the journey begins. Finally, EU policy in this field is aimed at preventing risks through harmonised technical requirements and roadside enforcement. How this policy is implemented through specific regulatory instruments is considered in the next section.

1.2. The three-tier model of cargo securing regulation in the EU

The regulation of cargo securing safety in Europe cannot be reduced to a single act or a single body. Analysis of the documents in force reveals three tiers, each with its own function (Fig. 1.1). The supranational tier consists of European Union acts that lay down mandatory requirements and enforcement procedures. The international coordination tier consists of the conventions and regulations of the United Nations Economic Commission for Europe (UNECE), which also extend to non-EU states.

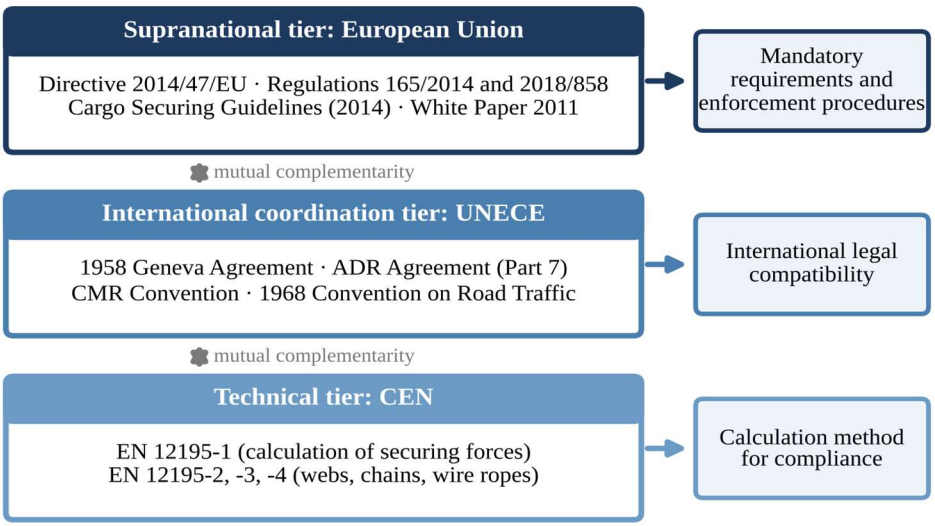


Fig. 1.1. **The three-tier model of cargo securing regulation in the EU**
Source: developed by the authors

The technical tier is represented by the standards of the European Committee for Standardization (CEN), above all EN 12195-1. This standard turns the general requirement that "the load must be securely fastened" into a calculation procedure.

*The European Union tier***.** The legal basis of EU transport policy is Title VI of the Treaty on the Functioning of the European Union. Under the principle of subsidiarity, the Union deals with matters on which the functioning of the single market and the safety of cross-border transport depend. The organisation of enforcement remains largely within the competence of the Member States.

The central act on the enforcement of cargo securing is Directive 2014/47/EU on the technical roadside inspection of the roadworthiness of commercial vehicles [13]. It replaced Directive 2000/30/EC and, for the first time, included the inspection of cargo securing among the items checked at the roadside. For this purpose, the directive contains a separate annex with inspection methods and assessment criteria for cargo securing. Deficiencies found are divided into three categories: minor, major and dangerous. In the case of a dangerous deficiency, further driving may be prohibited until it has been remedied. The value of this classification is that inspectors in different states assess the same violations in the same way, so that inspection results become comparable. The directive also introduces a risk-based selection system: vehicles of operators with a higher risk rating are inspected more often. It further sets requirements for the competence of inspectors. This last requirement is purely organisational only at first sight. Without uniform inspector training, uniform criteria are applied differently in practice.

Alongside binding acts, the European Commission uses soft-law instruments. In 2014, it published the European Best Practice Guidelines on Cargo Securing for Road Transport [18]. Formally, the guidelines are not binding. At the same time, they contain detailed practical recommendations on securing methods for different types of cargo, and the enforcement bodies of many states rely on them when assessing cargo securing. A non-binding document thus effectively serves as the industry benchmark.

The securing requirements are complemented by related acts. Regulation (EU) No 165/2014 on tachographs creates a body of data on speed and on the driver's driving and rest times [60]. These data do not concern securing directly, but harsh braking events recorded by the tachograph or by telematics can indicate episodes of increased load on the cargo. Regulation (EU) 2018/858 on

the approval and market surveillance of motor vehicles has applied since September 2020 [59]. It extends market surveillance to vehicles already in service. This matters for securing because securing options are determined by the body design: the number, location and strength of lashing points and the strength of the sideboards and headboard.

The UNECE tier. The United Nations Economic Commission for Europe differs from EU institutions in its wider geographical coverage. Its instruments are applied by states that are not members of the Union. For Ukraine, which is a party to a number of UNECE conventions, this has direct practical importance.

The legal mechanism of technical regulation within UNECE is the 1958 Geneva Agreement concerning the adoption of harmonised technical regulations for wheeled vehicles and the reciprocal recognition of approvals [72]. The UN Regulations adopted under it are developed and revised by the World Forum for Harmonization of Vehicle Regulations (WP.29). For the carriage of dangerous goods, the ADR Agreement is decisive. Its Part 7 contains requirements for the stowage of cargo and, in particular, for securing it against movement [74]. Formally, these requirements apply only to dangerous goods. The principles they embody are, however, of general significance: even distribution of mass, prevention of movement under inertial forces, and use of equipment appropriate to the mass and shape of the load.

The civil-law framework of international road carriage is set by the 1956 CMR Convention. It contains no technical requirements for securing but establishes the carrier's liability for loss of and damage to the goods. This liability indirectly encourages compliance with technical requirements, since proper securing is the cheapest way to avoid property claims. The provisions of the CMR are analysed in more detail in Section 1.3. The 1968 Convention on Road Traffic also belongs to this tier; its Article 30 deals with the loading of vehicles and requires the load to be arranged and, where necessary, secured so that it does not create danger [75].

The technical tier: EN 12195-1. EU acts define the required result, and UNECE conventions provide the international legal context. The standard EN 12195-1:2010, developed by CEN, answers the question of how this result is to be achieved [21]. This combination of a mandatory requirement with a voluntary technical instrument for meeting it distinguishes the European model from systems in which the state regulates not only the goal but also the means.

The standard is based on the equilibrium of forces acting on the cargo in a moving vehicle. The calculation is carried out separately for three directions

using standard acceleration coefficients. For road transport, these are 0,8 g forward, 0,5 g backward and 0,5 g sideways (for loads liable to tipping, 0,6 g is applied in the transverse direction). The standard distinguishes securing methods, each with its own calculation logic. Frictional (top-over) lashing increases the force with which the cargo presses on the deck and hence the friction force. Direct lashing counteracts the movement of the cargo directly. Blocking uses chocks and body elements, while bundling combines several units of cargo into one block.

The friction coefficient between cargo and deck has a special place in the standard. The standard gives its values for typical pairs of materials and a procedure for confirming them by testing. The choice of μ directly affects the required number of lashings. One practical consequence has been the widespread use of rubber anti-slip mats, which make it possible to reduce the number of lashings legitimately without reducing safety.

The standard is part of the EN 12195 series. Part 1 sets out the calculation principles, while Parts 2–4 contain requirements for securing equipment: web lashings made from man-made fibres (EN 12195-2), lashing chains (EN 12195-3) and steel wire ropes (EN 12195-4). This division makes it possible to update the requirements for individual devices without revising the calculation method.

The legal status of EN 12195-1 is twofold. Formally, the standard is voluntary, and no EU act obliges a carrier to apply this particular standard. In practice, a calculation performed according to the standard is regarded as sufficient proof of compliance with safety requirements. A carrier who has such a calculation does not have to prove that the chosen solution is safe. Without it, proving that the securing is safe is much more difficult.

Alongside EN 12195-1, the VDI 2700 guidelines of the Association of German Engineers continue to be used in Germany [77]. They describe certain industry-specific cases in more detail. Comparison of these documents shows the difference between the universal mathematical apparatus of the European standard and the stronger orientation of industry guidelines towards particular product types.

The 2010 standard also faces new challenges. These include electric trucks with a changed mass distribution, the carriage of components of wind and solar power plants with unusual geometry, and automated vehicles in which the driver’s traditional role in checking the securing is limited. In addition, field measurements call into question the universality of the standard acceleration coefficients. For category N1 vans, deceleration during emergency braking can

exceed 0,8 g [86]. On roads with poor surfaces, vertical and transverse accelerations of the cargo often exceed the standard values [79]. These results are used in Chapter 3 to justify the design margins.

Interaction between the tiers. The tiers described above developed incrementally, without a single design, but they complement each other functionally. None of them is self-sufficient. The directive's requirement for safe securing cannot be applied without a method that explains how to calculate it. A standard without a legal obligation remains a recommendation. UNECE conventions regulate contractual and procedural matters but not technical ones. This leads to a conclusion that matters for states harmonising their legislation with European law: transferring individual elements of the system without reproducing the links between them does not produce the expected effect.

It is useful to compare the European model with other jurisdictions. In the United States, requirements for protecting cargo against shifting and falling are set directly in the Federal Motor Carrier Safety Regulations (Part 393, Subpart I of Title 49 of the Code of Federal Regulations) [24]. The American model specifies the requirements in the regulation itself and relies less on voluntary standards. In Australia, the basic document is the Load Restraint Guide of the National Transport Commission, which combines features of a regulatory and a methodological document [49]. Compared with these, the European model is more flexible but harder for operators without special training to master.

The analysis also reveals internal tensions within the system. The first arises because the standard requires a quantitative calculation, which an inspector cannot perform during a roadside check. In practice, simplified visual criteria are therefore used, and the assessment of identical situations may differ between states. The second concerns the party responsible. In some legal systems, primary responsibility for securing lies with the driver, who must check it before departure; in others, with the consignor who loaded and secured the cargo. This divergence weakens the incentives to comply with the standard, because each party can rely on the other.

Prospects for the development of the system are linked to digitalisation. Smart tachographs, cooperative intelligent transport systems (C-ITS) and lashing equipment with built-in tension sensors create a technical basis for moving from periodic checks to continuous monitoring. The regulatory framework for such monitoring is still taking shape. Yet the very possibility of obtaining real-time data on the state of securing also changes the approach to assessing delivery reliability. We return to this question in Chapters 7 and 8.

1.3. The legal framework of cargo integrity

Technical securing rules determine how to prevent cargo from shifting. The question of who is liable for the consequences, and to what extent, is settled by contract law. Unlike reliability, which logistics has borrowed from engineering, cargo integrity has a long legal history: the basic institutions of transport law developed precisely around the carrier's duty to deliver the goods intact. For our study, this has a twofold significance. On the one hand, legal rules set the limits of liability and the procedures for recording cases of loss or damage, and so create a documentary basis for recording them. On the other hand, legal logic is aimed at allocating liability after the event rather than at assessing the chain's ability to avoid such events.

In international road transport, the decisive instrument is the 1956 Convention on the Contract for the International Carriage of Goods by Road (CMR). Its parties include Ukraine, Poland and the other states through which the routes considered in this monograph pass [11]. Four articles of the Convention are of particular importance here:

Article 17 establishes the carrier's liability for total or partial loss of the goods and for damage occurring between the time when the carrier takes over the goods and the time of delivery, as well as for delay in delivery, except in the circumstances specified by the Convention;

Article 20 introduces a presumption of loss: the goods are deemed lost if they have not been delivered within 30 days of the agreed time limit or, if no time limit was agreed, within 60 days of being taken over;

Articles 23 and 25 determine the amount of compensation. In the case of loss, it is calculated by reference to the value of the goods but may not exceed 8,33 units of account per kilogram of gross weight. In the case of damage, the amount by which the goods have diminished in value is compensated;

Article 30 distinguishes between loss and damage that are apparent on delivery and those that are not. For non-apparent loss or damage, the consignee must send reservations within seven days of delivery, Sundays and public holidays excepted.

The provision of Article 30 has an indirect but important significance for reliability theory. The Convention in effect recognises two classes of loss and damage events that differ in the moment of detection: those established at the point of handover and those discovered after the carriage has been completed. In

the terms of reliability theory, this corresponds to the distinction between evident and hidden failures. For hidden failures, indicators that record the outcome at the moment of delivery are inherently incomplete.

In 2008, the Additional Protocol to the CMR concerning the electronic consignment note was adopted in Geneva [73]. A consignment note issued in accordance with the Protocol has the same evidential value as a paper one. This creates a legal basis for automated recording of the condition of the cargo and of reservations at the moment of handover.

The national laws of states applying the CMR reproduce a similar structure for domestic carriage. Under Article 65 of the Polish Transport Law (Prawo przewozowe), the carrier is liable for loss, shortage or damage of the consignment from acceptance to release, as well as for delay.

The carrier can be released from liability only by proving that the damage occurred for reasons attributable to the consignor or consignee, owing to the properties of the goods or as a result of force majeure [76]. Like the CMR, national law links integrity to two dimensions: quantitative (loss, shortage) and qualitative (damage, loss of value).

For carriers operating on the EU market, cargo integrity requirements are not limited to contract law. As shown in Section 1.2, preventing cargo from shifting is also a public-law road safety requirement that is checked during roadside inspections. At the level of management systems, international standards provide the basis. ISO 31000 establishes the principles and process of risk management [30]. ISO 28000 specifies requirements for security management systems, including in supply chains, with an emphasis on countering intentional threats [31].

The legal framework of cargo integrity therefore consists of three layers: contractual (carrier liability), public-law (road safety requirements, including those on securing) and standards-based (risk and security management systems). The documents that accompany each of these layers (consignment notes, acceptance reports, reservations, inspection reports) contain information from which one can assess not only individual cases of loss or damage but also the chain's overall ability to prevent them. This idea is the starting point for Chapters 2 and 7.

1.4. Ukrainian regulation and the harmonisation gap

Ukraine is in a special position here. It is a party to the CMR, the 1958 Geneva Agreement, the ADR Agreement and the Convention on Road Traffic, and is therefore already integrated into the international coordination tier described in Section 1.2. The 2014 Association Agreement with the EU [2] and the candidate status granted in June 2022 oblige Ukraine to bring its transport legislation closer to Union law. On 1 October 2022, Ukraine acceded to the Convention on a Common Transit Procedure [67]. Approximation at the level of cargo securing requirements is proceeding more slowly.

The basic requirements for the carriage of goods in Ukraine are contained in the Law of Ukraine "On Road Traffic" [42], the Law of Ukraine "On Road Transport" [41], the Road Traffic Rules approved by Resolution of the Cabinet of Ministers of Ukraine No. 1306 of 10 October 2001, and the Rules for the Carriage of Goods by Road in Ukraine approved by Order of the Ministry of Transport of Ukraine No. 363 of 14 October 1997 [48]. Section 22 of the Road Traffic Rules requires the driver to check, before setting off, that the cargo is reliably placed and secured, and to monitor it while driving so as to prevent it from falling, dragging or causing other dangerous consequences [6].

The requirement is formulated as an obligation of result. No regulatory method is laid down by which the driver or consignor should determine whether the securing is sufficient.

The authors' analysis of regulatory documents makes it possible to compare the main requirements underlying the European model with current Ukrainian practice (Table 1.1).

The table reflects the authors' expert assessment. It does not claim to be a complete legal audit and is intended to outline the directions of harmonisation.

The comparison makes it possible to group the harmonisation problems into three types of inconsistency.

The regulatory and technical inconsistency arises between the general requirement that "the load must be securely fastened" and the absence of a regulated way of checking compliance with it. The driver is formally responsible for the result but has no tool for assessing it.

Table 1.1 **Comparison of elements of the European cargo securing regulation model with Ukrainian practice**

Element of the European model	Main EU document	Status in Ukrainian practice (authors' assessment)
Inspection of securing as part of roadside enforcement, with classification of deficiencies	Directive 2014/47/EU	A securing requirement exists, but a uniform classification of securing deficiencies by severity is not established in regulation
Calculation method for sufficiency of securing	EN 12195-1	The method has no regulatory status; its use depends on the carrier's initiative
Documentation of the securing calculation	EU Guidelines (2014)	There is no mandatory document recording the securing method and design parameters
Requirements for lashing equipment and its marking	EN 12195-2, -3, -4	Equipment of varying quality is on the market; in-service checks of its conformity are limited
Division of responsibility between consignor and carrier	National legislation of EU Member States	The allocation of securing duties depends mainly on contract terms
Special securing training for drivers and loaders	Directive (EU) 2022/2561 (driver qualification)	Cargo securing is covered only fragmentarily in driver training programmes
Risk-based selection of vehicles for inspection	Directive 2014/47/EU	Elements of a risk-based approach are being introduced gradually

Source: developed by the authors

The institutional inconsistency lies in the fact that securing can be checked during roadside inspections only by visual signs, and there are no uniform assessment criteria similar to the European classification of deficiencies. As a result, identical situations may be assessed differently.

The behavioural inconsistency concerns incentives. If the cost of full compliance with the standard (additional lashings, anti-slip mats, time for calculation and training) exceeds the expected penalties, the carrier rationally chooses minimal securing. This inconsistency can be overcome in two ways: by tightening enforcement or by showing that proper securing pays for itself through reduced losses. The monograph develops the second way. Chapter 5 shows the economic effect of the improved method, and Chapter 8 assesses securing as a measure for increasing supply chain reliability.

The experience of the states that joined the EU in 2004–2007 shows that formal transposition of European acts does not in itself change the practice of market participants. Change occurs when the rule is accompanied by tools for applying it: methods, training programmes and internal control procedures. Harmonisation in the field of securing is therefore best seen as a sequence of three steps: establishing the requirements in regulation, creating methodological support and changing the behaviour of market participants through training and economic incentives.

On the basis of this analysis, three research questions were formulated that shape the rest of the book:

– how to turn the general requirement for secure fastening into a calculation procedure suited to Ukrainian road conditions and understandable to company staff (Chapters 3–5);

– how to assess the contribution of securing and other measures to cargo integrity at the level of the whole supply chain rather than a single journey (Chapters 2 and 6–8);

– which organisational mechanisms ensure genuine rather than formal implementation of the methods developed (Chapter 9).

1.5. Research methodology

The subject of the monograph lies at the intersection of several disciplines: transport law, mechanics, reliability theory and logistics management. Each has its own methods and its own idea of what counts as evidence. A lawyer relies on the text of a rule and the practice of its application, an engineer on equilibrium equations and measurement results, a logistician on consignment statistics and performance indicators.

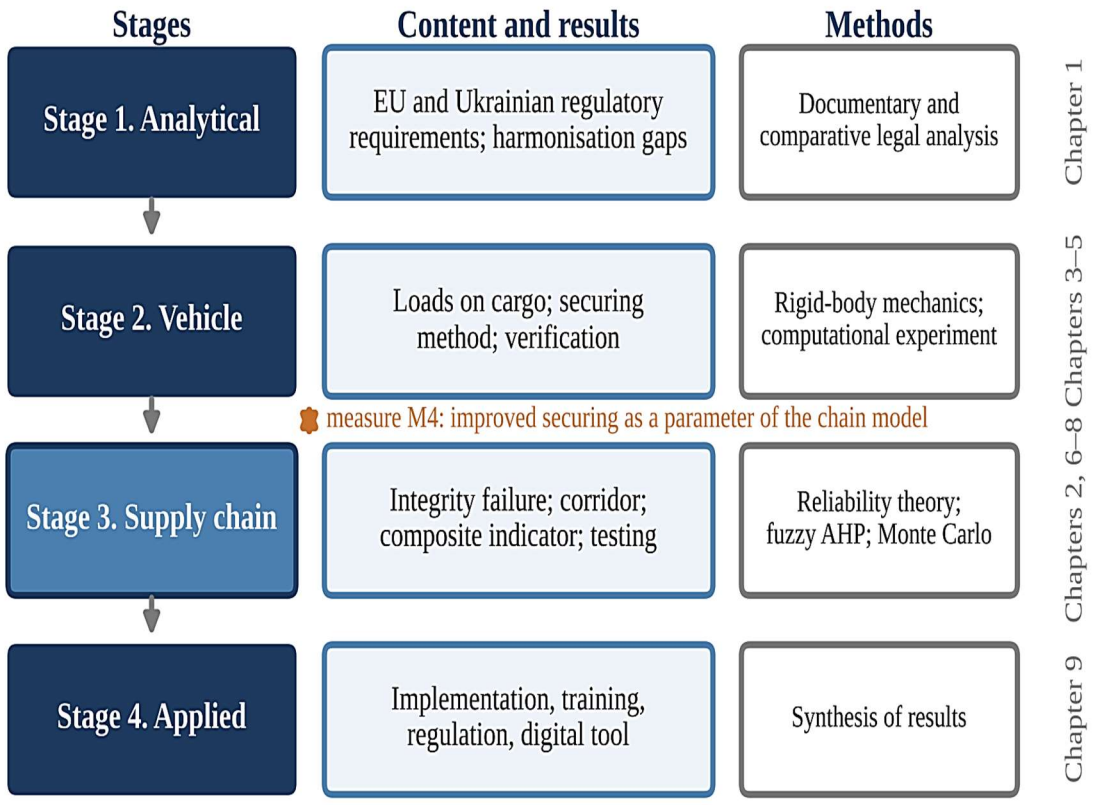


Fig. 1.2. **Logic of the study**

Source: developed by the authors

The research methodology therefore had to be built so that the results of one level of analysis could be used at another without loss of meaning. The overall logic of the study is shown in Fig. 1.2.

The study consists of four stages.

The first stage is analytical. Its task is to identify the regulatory requirements for cargo securing and cargo integrity and the gaps between European and Ukrainian regulation. At this stage, documentary analysis of EU acts, UNECE conventions, CEN standards and Ukrainian legislation was used, together with comparative legal analysis.

The output of the stage is a list of requirements that the method must satisfy and a list of inconsistencies that it must help to overcome (Section 1.4).

The second stage concerns the vehicle level. Here the apparatus of classical mechanics is applied: the equations of rigid-body statics, Coulomb's law of friction and moment equilibrium conditions. The empirical basis consists of published results of field measurements of cargo accelerations carried out by

other researchers. The authors did not perform their own field measurements at this stage. All parameters missing from published sources are therefore marked as design assumptions and included in the sensitivity analysis (Section 5.5).

The third stage concerns the supply chain level. Here reliability theory (the exponential failure model and fault trees), the methodology of composite indicator construction, the fuzzy analytic hierarchy process and the desirability scale are used. The indicator was tested by statistical simulation on a model chain whose parameters are consistent with open data on the cross-border corridor.

The fourth stage is applied. Its outputs are an implementation roadmap, tools for choosing the securing method, a training programme and proposals on regulation.

The link between the second and third stages works both ways. The securing method determines how far the probability of mechanical damage and of loosened securing during the driving stages is reduced. These quantities enter the stage model of the chain as parameters of measure M4. Conversely, the chain model makes it possible to assess when investment in improved securing is preferable to other measures and when it is not.

The sources of input data and their status are summarised in Table 1.2.

The principle followed throughout the monograph is simple: every figure in the text either has a reference to a verified source or is marked as having been calculated by the authors under explicitly stated assumptions.

The scope of the study should be stated separately. The concept of safety is used in the monograph in a narrow sense, namely as the safety of cargo placement and securing and the integrity of the cargo during carriage. Protection of cargo against theft is considered only insofar as it affects the integrity reliability of the chain. The calculations were performed for road vehicles of category N3 with a flatbed or curtainside platform.

The specific features of category N1 vans, for which braking deceleration may exceed the standard values, are mentioned but were not modelled separately. Multimodal chains with rail or sea legs are left for further research.

Table 1.2 **Sources of input data and their status**

Data group	**Source**	**Status**	**Where used**
Accident and traffic volume statistics for the EU	European Commission, ERSO, Eurostat	Official published data	Section 1.1
Regulatory requirements for securing and liability	EU directives and regulations, UNECE conventions, EN 12195-1, Ukrainian acts, Polish law	Texts of regulatory documents	Chapters 1, 2, 4, 9
Cargo accelerations under real driving conditions	Peer-reviewed papers on field measurements	Published results of other authors, with references	Chapter 3, Section 4.1
State of the corridor (crossing points, queues, blockades, theft, legal regime)	Official announcements, TAPA reports, trade media	Published data, with references	Chapter 6, Section 8.1
Parameters of the securing method (k_u, δ_{max}, k_w, k_t, k_f, Z_{req})	Authors' justification	Design assumptions tested by sensitivity analysis	Chapters 4, 5
Parameters of transport scenarios and of the chain model	Authors' justification	Scenario assumptions	Chapters 5, 8
Results of calculations and simulation	Authors' calculations in Python	Original results	Chapters 3–5, 7, 8, appendices

Source: developed by the authors

Conclusions to Chapter 1

Road crashes involving heavy goods vehicles account for about 14 % of all road deaths in the EU, and only about one in eight of those killed was inside the truck. Cargo securing is among the risk factors that can be managed before the journey begins, which is why EU requirements for it are a matter of public law and are checked during roadside inspections.

Cargo securing regulation in the EU follows a three-tier model. Union acts lay down mandatory requirements and enforcement procedures, UNECE instruments ensure the international legal compatibility of approaches, and EN 12195-1 turns the requirement for secure fastening into a calculation method. The effectiveness of the model depends on the links between the tiers, so transferring individual elements without these links does not produce the expected result. The twofold status of EN 12195-1, formally voluntary but in practice a benchmark document, creates a presumption of compliance for a carrier who has a documented calculation. At the same time, published field measurements of accelerations show that the standard coefficients do not cover all real conditions, which justifies the need for design margins on roads with a degraded surface.

The legal framework of cargo integrity is formed by contractual, public-law and standards-based layers. The distinction between apparent and non-apparent loss in Article 30 of the CMR Convention corresponds to the division of failures into evident and hidden ones, which underlies the classification of integrity failures in Chapter 2.

Ukrainian regulation contains a general requirement for secure fastening but does not establish a method for checking compliance with it. The harmonisation problems are grouped into regulatory and technical, institutional and behavioural inconsistencies. Overcoming them requires combining regulatory change with methodological support, staff training and an economic case for the measures. The research methodology is designed so that the results of the vehicle-level analysis can be used at the supply chain level, and every figure in the text either has a reference to a verified source or is marked as calculated by the authors under explicitly stated assumptions.

CHAPTER 2.

CARGO INTEGRITY AS A DIMENSION OF SUPPLY CHAIN RELIABILITY

2.1. Development of research approaches to supply chain reliability

In Chapter 1, cargo integrity was considered from a legal point of view, as a matter of liability and enforcement. For logistics research this is not enough. A cargo owner compares chains first of all by their ability to deliver goods in proper condition. Who will be liable for a loss is a secondary question. To measure this ability, integrity has to be placed within the category of reliability. We therefore first trace how this category developed in supply chain research.

The concept of reliability came to logistics from the reliability theory of technical systems. In that theory, reliability is defined as the ability of an item to keep, over time and within specified limits, the values of the parameters that characterise its capacity to perform the required functions under given conditions.

The toolkit of the theory, systematised in particular by M. Rausand and A. Høyland, includes the probability of failure-free operation, mean time to failure, failure rate, availability and maintainability measures [58].

The structure of a complex system is described by series, parallel and mixed arrangements of elements. It is precisely this logic, according to which a system works only when a certain set of its elements works, that proved convenient for describing a supply chain as a sequence of links, the failure of any one of which disrupts order fulfilment. Four research streams on supply chain reliability can be distinguished, each with its own subject and conceptual framework.

Transfer of classical reliability theory. One of the first systematic steps in this direction was the work of M. Thomas. He considered supply chain reliability for contingency operations, where the main criterion is guaranteed accomplishment of the logistics task rather than economic efficiency [69].

X. Jia, L. Cui and L. Xing compared the definitions of reliability in classical theory and in supply chains, described typical reliability structures of chains and showed how the chain reliability problem can be reduced to a classical one and solved by known methods [34]. V. Lukinskiy and co-authors noted that failure models covering a set of logistics operations are insufficiently developed and that in practice reliability is increased mainly by creating redundant resources, above all inventory [44].

Supply chain risk management. This stream developed largely independently of the previous one. U. Jüttner, H. Peck and M. Christopher linked chain risk to sources in the external environment, within the chain itself and in its organisational structure [35].

C. Tang systematised quantitative models, distinguishing operational risks (uncertainty of demand, supply and cost) from disruption risks caused by natural disasters, man-made events or deliberate acts [68].

P. Kleindorfer and G. Saad proposed a conceptual framework for managing disruption risks [36], and S. Wagner and C. Bode empirically examined the relationship between individual dimensions of risk and chain performance [80].

In this tradition, loss of or damage to cargo appears as a manifestation of a realised risk but not as a measurable state of the chain. Supply chain resilience. After the COVID-19 pandemic and the wartime shocks in Europe, this stream gained particular weight. M. Christopher and H. Peck treated resilience as the ability of a system to return to its original or a better state after a disturbance [9].

Y. Sheffi and J. Rice linked it to redundancy and flexibility [64]. S. Ponomarov and M. Holcomb defined resilience through the chain's ability to prepare for unexpected events, respond to disruptions and recover [57].

Quantitative methods of resilience analysis are summarised in the review by S. Hosseini, D. Ivanov and A. Dolgui [28]. D. Ivanov provided a simulation-based assessment of the consequences of large-scale epidemic disruptions for global chains [32]. The resilience concept added the time dimension of recovery to the reliability approach. Its subject, however, remains flow characteristics (volumes, lead times, capacity availability) rather than the physical condition of the cargo.

Reliability of transport and logistics systems in the Polish and Ukrainian schools. T. Nowakowski, analysing the modelling of transport network reliability, noted that the growing share of highly processed products in freight flows raises the value of cargo and, accordingly, customers' requirements for cargo safety and delivery reliability. Among the typical errors in performing a transport task, he named, in particular, destruction of or damage to the consignment [54].

This position can be regarded as the germ of the idea of integrity as a component of reliability, but it was not developed into a separate indicator.

A team including O. Zagurskiy, in a monograph prepared together with Polish researchers, critically analysed methods of assessing supply chain reliability and adapted the concepts of time to first failure, technical life and redundancy to logistics systems [85]. Methods of supply chain reliability management are also discussed in [84], and methods of improving it in [83].

The study by L. Savchenko, O. Zagurskiy and S. Bondariev systematised the sources of risk to cargo integrity in road transport and showed that preserving cargo depends on the coordinated actions of all participants in the carriage process [63]. This monograph continues both lines of research.

D. Kumar, G. Soni, Y. Kazancoglu and A. Rathore attempted to summarise the state of research. Having selected 45 peer-reviewed publications, they found that the vast majority of studies are mathematical or conceptual and that empirical research is lacking [38].

This finding explains why chain reliability models contain almost no integrity-related failures. Analysing such failures requires data on claims, discrepancy reports and temperature logs, which rarely enter open scientific circulation. The overall trend can be described as a widening of the subject of reliability: from the structural operability of the chain to its ability to withstand risks and recover.

A comparison of the streams is given in Table 2.1.

Table 2.1 **Research streams on supply chain reliability and the place of cargo integrity in them**

Stream	Subject	Core concepts	Typical indicators	How integrity is taken into account
Transfer of classical reliability theory	The chain as a system of links	Failure, operable state, connection structure	Probability of failure-free operation, mean time to failure, availability	Implicitly, as one of the causes of link failure
Risk management	Sources and consequences of uncertainty	Risk, risk source, disruption	Probability and consequences of a risk event, risk matrices	As a type of operational or disruption risk
Resilience	Chain behaviour during and after a disturbance	Readiness, response, recovery	Recovery time and recovery losses	Largely disregarded; the focus is on flows and capacity
Reliability of transport and logistics systems	The transport process as a human – machine – environment system	Transport process failure, service life, redundancy	Reliability indicators of individual operations and of the chain	Recognised as significant but not formalised as a separate indicator

Source: compiled by the authors

The physical condition of the cargo, which is the final result of any supply chain, has remained at the periphery of this development. To fill the gap, the category of integrity itself must first be clearly defined.

2.2. Conceptual framework of cargo integrity

In regulatory and research sources, the Ukrainian terms for cargo preservation, cargo integrity, cargo safekeeping and loss of integrity are often used as synonyms. Such vagueness is unacceptable when constructing a quantitative indicator. We propose distinguishing four concepts according to the nature of the category and its bearer (Table 2.2).

Table 2.2 **Distinction between concepts related to cargo integrity**

Concept	Content	Nature of the category	Bearer
Cargo preservation	The set of technical, technological and organisational measures taken by participants in the carriage process to prevent loss, shortage, damage or spoilage of the cargo	Activity	Chain participants
Cargo integrity	The state of the cargo in which its quantitative and qualitative characteristics at the moment of handover to the next participant correspond to the accompanying documents and the contract within permissible deviations	State, result	Cargo
Loss of integrity	An event as a result of which the state of integrity is violated: loss, shortage, damage, spoilage	Event	Cargo and the responsible participant
Integrity-oriented reliability of the supply chain	The ability of the chain to ensure cargo integrity at all stages of movement over a given period under specified conditions	Property of the system	Supply chain

Source: developed by the authors

This distinction separates what the chain does (preservation) from the result it achieves (integrity) and from the capability it shows over time (integrity-oriented reliability). The last category has so far had no separate definition in the literature and is the subject of assessment in Chapters 7–8. The definition has one more consequence: permissible deviations, above all natural loss norms and technological tolerances, are not loss-of-integrity events and should not reduce the value of the reliability indicator.

There is a direct link between the concepts of preservation and cargo securing, to which Chapters 3–5 are devoted. Securing is one of the most important preservation measures during the driving stages. Its quality affects the probability of mechanical damage to the cargo and, through it, the integrity reliability of the chain as a whole. This link is described quantitatively in Chapter 8.

Alongside legal sources, empirical knowledge of the factors behind loss of integrity is important for defining the content of the category. D. Ekwall and B. Lantz, analysing the incident database of the Transported Asset Protection Association (TAPA) for Europe, the Middle East and Africa, found that cargo theft follows seasonal patterns by month and day of the week, and that these patterns differ between locations in the transport chain [15]. On a larger set of global TAPA data, the same authors confirmed annual and weekly seasonality for most incident types [16]. For perishable goods, the leading factor of qualitative loss of integrity is breach of the temperature regime. The review by N. Ndraha and co-authors showed how widespread such breaches are in food cold chains in different countries [50]. S. Mercier and co-authors analysed time–temperature conditions at each critical stage of the cold chain [46]. An important conclusion for indicator design follows from these studies: the factors of loss of integrity are distributed unevenly both in time and across the stages of the chain. An assessment of reliability must therefore take into account both the frequency and the location of failures.

2.3. Limitations of common supply chain performance indicators

The methodology of supply chain performance measurement took shape at the intersection of logistics, operations management and management accounting. As early as the late 1990s, B. Beamon showed that a measurement system cannot

rely on a single indicator and must cover at least resources, output and flexibility [4]. A. Gunasekaran, C. Patel and R. McGaughey divided indicators into strategic, tactical and operational levels and stressed the need to align them with the goals of all chain participants [26]. Both concepts imply a requirement that is essential for our study: the indicator must be measured at the level of individual operations and aggregated at the level of the whole chain.

In practice, the most common framework is the SCOR reference model, which now exists as the digital standard of the Association for Supply Chain Management [3]. According to the analysis by S. Huan, S. Sheoran and G. Wang, the model's metrics are grouped by performance attributes, among which reliability is represented primarily by the perfect order fulfilment metric [29]. An order is considered perfect if it is delivered complete, on time, undamaged and with correct documentation. The metric equals the share of such orders in the total.

The difficulties with this metric were noticed while it was still being adopted. R. Novack and D. Thomas, summarising the experience of companies that introduced perfect order measurement, identified three problems: what exactly counts as a perfect order; how to organise measurement, which requires coordination between the transport, warehouse and accounting functions; and how to use the results to improve performance [53]. The first of these problems relates directly to integrity. Each company draws the line between a "damaged" and an "undamaged" order in its own way, so the values of the metric for different chains are hard to compare.

Even more widely used is OTIF (on time, in full), the share of orders delivered on time and in full [8]. Its simple calculation has made it a standard in retail supply contracts, but the same simplicity limits its use. In most interpretations, "in full" refers to quantity. The qualitative condition of the cargo is either ignored or taken into account indirectly, when the consignee rejects damaged products.

The indicators considered have five limitations as regards the assessment of integrity:

– binary nature. At the order level, a loss-of-integrity event is either recorded or not. The severity of the event, i.e. the share of value lost, is not reflected in the value of the indicator;

– moment of measurement. The indicator is determined at delivery, so hidden damage and spoilage discovered later, in particular within the seven-day

period under Article 30 of the CMR, are either not reflected or reflected with a delay through claims;

–no time structure. The indicators contain no information on the frequency and regularity of loss-of-integrity events, i.e. on the interval between failures, which is one of the basic parameters in reliability theory;

– no measure of response. The chain's ability to detect a violation and limit its consequences, for example to intervene in a temperature excursion before the cargo is finally spoiled, is not taken into account;

– no localisation. Aggregation at the order level hides the stage at which the failure occurred, which rules out targeted management.

The first limitation can be illustrated by a hypothetical example. Suppose two chains each fulfilled 2 000 orders of equal value V in a year, and in each chain 80 orders were found to be imperfect. The perfect order metric for both chains equals 96 %. In the first chain, 15 of the imperfect orders have minor damage with an average loss of 3 % of value. In the second chain, of the 15 orders with signs of loss of integrity, 4 involve complete spoilage of perishable cargo and 11 have the same minor damage. The total value lost in the first chain is 15 0,03V = 0,45V, or 0,023 % of the value of the goods carried. In the second chain it is $4 \cdot 1{,}0V + 11 \cdot 0{,}03V = 4{,}33V$, or 0,217 %. With the same value of the metric, losses in the second chain are almost ten times higher. The metric does not distinguish between chains that have fundamentally different reliability from the cargo owner's point of view.

How far common indicators meet the requirements for assessing integrity reliability is summarised in Table 2.3. The comparison also includes the damage claims ratio used by carriers and insurers.

None of the indicators meets most of the requirements. The damage claims ratio, which is closest in content, is reactive and reflects only cases that have been formalised legally. Assessing integrity reliability therefore requires not a modification of one of the existing indicators but a separate system of partial indicators with subsequent aggregation. Such an indicator is constructed in Chapter 7.

Table 2.3 **Compliance of common indicators with the requirements for assessing integrity reliability**

Requirement for the indicator	OTIF	Perfect order fulfilment (SCOR)	Damage claims ratio
Recording the fact of loss of integrity	Partly, quantitative shortage only	Yes	Yes
Severity of consequences (share of value lost)	No	No	Partly, through the amount claimed
Hidden failures discovered after delivery	No	No	Yes, with a delay
Frequency of failures and interval between them	No	No	No
Chain stage at which the failure occurred	No	No	Partly
Ability to detect a violation and limit its consequences	No	No	No
Sensitivity to external disruptions	No	No	No

Source: developed by the authors

2.4. Integrity failure: definition, classification and basic model

To apply the apparatus of reliability theory to integrity, one must first define what counts as a failure. In classical theory, a failure is an event consisting in the loss of the operable state of an item [58]. In supply chain reliability models, a failure is usually taken to be a link's non-performance of its function within the specified time or in the specified volume [34, 44]. For integrity, this definition is not enough, since the goods may arrive on time and in full but in an unusable condition.

We propose the following definition. A cargo integrity failure is an event as a result of which the quantitative or qualitative characteristics of the cargo at the moment of handover to the next chain participant or to the final consignee deviate from those recorded in the accompanying documents and the contract beyond the permissible limits.

The key feature of this definition is that the failure is tied not to the completion of an order but to each act of handing the cargo over between participants. This makes it possible to localise the failure by chain stage and makes the concept consistent with the legal principle of carrier liability from taking over the goods until their delivery [11, 76]. Depending on the nature of the deviation and the moment of detection, integrity failures are classified as shown in Table 2.4.

Table 2.4 **Classification of cargo integrity failures**

Failure type	Criterion	Typical manifestations	Moment of detection	Counterpart in reliability theory
Total	The cargo or a load unit is lost completely	Theft, destruction in a crash or fire, complete spoilage	At delivery or by presumption of loss (CMR Art. 20)	Complete failure
Partial quantitative	The actual quantity is below the documented quantity beyond loss norms	Missing packages, short weight, partial theft	At acceptance by quantity	Partial failure
Qualitative, apparent	Visible changes in condition that reduce value	Mechanical damage to packaging and cargo due to shifting, wetting, deformation	At acceptance by quality	Partial failure with degraded parameters
Qualitative, hidden	Changes in condition not detected at acceptance	Internal damage, consequences of temperature breaches	After delivery, within the reservation period (CMR Art. 30)	Hidden failure
Pre-failure state	Breach of carriage conditions without confirmed loss	Temperature excursion, broken seal, loosened securing, exceeded permissible dwell time	From monitoring data or checks during carriage	Pre-failure state, parameter degradation

Source: developed by the authors

The classification separately includes a pre-failure state, i.e. a breach of carriage conditions that has not yet led to a confirmed loss but substantially increases the probability of failure. In modern chains, it is precisely such events that make up the bulk of information for proactive management: a short temperature excursion recorded by a logger, a broken seal without shortage, a loosened lashing found during an en-route check.

The classification makes it possible to describe the chain as a system of stages connected in series, each with its own probability that the cargo passes through it without an integrity failure. Assuming that failures at different stages are independent, the probability of delivery without an integrity failure equals the product:

$$P_{int} = \prod_{i=1}^{n} p_i, \tag{2.1}$$

where P_{int} is the probability of delivering the cargo without an integrity failure;

p_i is the probability of passing stage i without an integrity failure;

n is the number of stages (loading, driving, waiting at the border, inspection, unloading, etc.).

Even this simplified model reveals an important regularity: with high reliability at each stage, chain reliability decreases noticeably as the number of stages grows (Fig. 2.1).

If each of seven stages ensures integrity with probability 0,995, the probability for the chain as a whole is $0,995^7 \approx 0,966$, so roughly one consignment in thirty suffers a failure. With a stage probability of 0,99, the value for seven stages falls to 0,932, so one consignment in fifteen fails.

Model (2.1) has significant limitations. It does not take into account the severity of failures, does not distinguish between evident and hidden failures, ignores the interdependence of stages and does not reflect the chain's ability to detect and localise violations. Interdependence is especially important. A long dwell at the border increases the probability of a qualitative failure at later stages, and poor securing during loading shows up as damage only after several hundred kilometres of driving. These limitations justify the need for a composite indicator that combines several partial components.

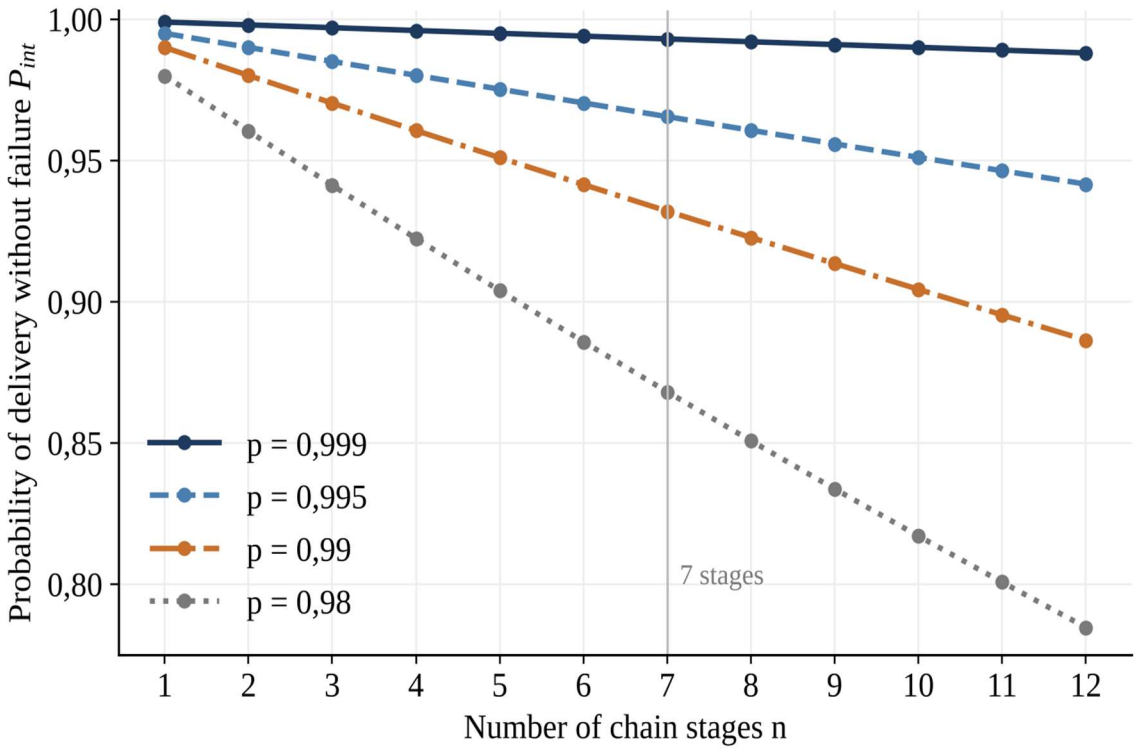


Fig. 2.1. **Probability of delivery without an integrity failure as a function of the number of chain stages**

Source: developed by the authors

The analysis makes it possible to formulate the research gap addressed by the second part of the study. A developed apparatus exists for assessing chain reliability by time and quantity criteria, and a legal and empirical description of loss-of-integrity events also exists. What is missing is a methodological approach that would allow the chain's ability to ensure cargo integrity to be assessed quantitatively as a separate dimension of reliability. Such an approach must take into account the frequency, severity and location of failures, the chain's ability to detect them and its sensitivity to external disruptions.

2.5. Documentation support for recording integrity failures

An integrity failure can be taken into account only if it has been recorded in a document. Whether integrity reliability can be assessed at all therefore depends on which documents accompany the cargo and what the chain participants write in them. Let us consider how the condition of the cargo is documented in

international road carriage and which elements of this documentation are suitable for calculating reliability indicators.

The main document is the CMR consignment note. Under Article 8 of the Convention, on taking over the goods the carrier must check the accuracy of the statements in the consignment note as to the number of packages, their marks and numbers, and the apparent condition of the goods and their packaging [11]. If the carrier has no reasonable means of checking these particulars, reasoned reservations are entered in the consignment note. In the absence of reservations, it is presumed that the goods were in good condition when taken over (Article 9).

The first act of handover, from consignor to carrier, thus already has a legal procedure for recording condition. It corresponds to the boundary between stages E1 and E2 in the chain model.

The consignee's reservations are governed by Article 30. If loss or damage is apparent, the reservation is made at delivery. If it is not apparent, the reservation must be made within seven days of delivery, Sundays and public holidays excepted. Articles 8 and 30 together set the start and end points between which the carrier is liable. Between them, at the intermediate stages, the Convention establishes no mandatory procedures for recording the condition of the cargo. This is where the information gap discussed in Section 6.3 arises: a failure that occurred at the border is legally recorded only at unloading.

The electronic consignment note introduced by the 2008 Additional Protocol [73] technically makes it possible to close this gap. Entries can be made at each stage, for example during a border inspection or after re-securing the cargo, with a time stamp and the author's identification. The Protocol itself, however, does not require such intermediate entries. Their content and frequency depend on agreements between the chain participants. Besides the consignment note, the condition of the cargo is recorded in other documents. Their list and their suitability for calculating the components of the reliability indicator are given in Table 2.5.

The table shows that the documents needed to calculate all five components already exist in practice. The problem lies elsewhere: they belong to different chain participants and are kept in different systems. Loading reports are held by the consignor, telematics records by the carrier, queue data by the system operator, acceptance reports by the consignee and claims by the insurer. Assessing reliability therefore requires not new documentation but an agreement on exchanging existing data and linking them to a specific consignment through a common identifier, such as the consignment note number.

Table 2.5 **Documents recording the condition of the cargo and their use in assessing integrity reliability**

Document	Stage	What it records	Failure type (Table 2.4)	Indicator component
CMR (e-CMR) consignment note with carrier's reservations (Art. 8)	E1	Number of packages, apparent condition of cargo and packaging when taken over	Reference point for all types	All component, as the baseline for comparison
Loading report, securing calculation sheet	E1	Stowage plan, securing method and equipment, cargo temperature	Partial quantitative, qualitative apparent	K_P (stage E1)
Telematics and temperature logger records	E2–E5	Driving pattern, harsh braking, temperature, door openings	Pre-failure state, qualitative hidden	K_D, K_P (time-dependent stages)
En-route securing inspection report	E2, E5	Lashing tension, cargo displacement	Pre-failure state	K_D
Inspection report, seal numbers, NCTS records	E4	Opening of the cargo space, seal replacement, inspection duration	Pre-failure state, partial quantitative	K_D, K_P (stage E4)
Electronic queue data	E3	Registration and call times, waiting time	Factor of qualitative failures	K_R
Report of acceptance by quantity and quality, consignee's reservations (Art. 30)	E7	Discrepancies in quantity and quality, apparent and hidden	All types	K_P, K_S, K_T
Claim, calculation of compensation (Arts. 23, 25)	After E7	Value of losses and loss of value	All types	K_S

Source: developed by the authors on the basis of [11, 73]

Two documents in Table 2.5 are rarely found in the practice of Ukrainian carriers: the securing calculation sheet and the en-route securing inspection report. Both are linked to the method set out in Chapters 4–5, and templates of them are given in Appendices A and B. Importantly, they serve a dual purpose. For the carrier, they are evidence of proper securing in the event of a liability dispute. For reliability assessment, they are a source of information on pre-failure states, without which the detection and response component cannot be calculated.

The question of how to distinguish an integrity failure from permissible deviations requires separate consideration. For bulk and liquid cargo, there are natural loss norms; for perishable products, tolerances for quality deterioration during the storage period. Deviations within these norms are not failures (Section 2.2). For packaged general cargo, there are usually no permissible quantity deviations, and for damage the threshold is set by the contract or by the consignee's internal rules. It is therefore advisable to enter every recorded discrepancy in the consignment register and to decide whether it is a failure according to criteria agreed in advance. The structure of such a register is given in Appendix D.

2.6. Integrity reliability and cargo owner losses

Is the composite indicator constructed in Chapter 7 related to the cargo owner's monetary losses? The answer matters for two reasons. If there is no relationship, the indicator risks becoming an assessment for its own sake, unconnected with the economic interests of the chain participants. If the relationship is complete, the indicator could be replaced by a simpler quantity, namely expected losses. Let us consider how these two characteristics relate to each other, using the simulation results presented in Chapter 8 and Appendix E.

For 32 combinations of measures in the perishable goods chain, the correlation coefficient between the expected value of the indicator and the expected losses from loss of integrity is –0,73; for 8 combinations in the non-perishable goods chain, it is –0.89. The relationship is thus strong and has the expected direction: higher reliability corresponds to lower losses. At the same time, it is far from functional. In the perishable goods chain, a linear relationship explains only about half of the variability of losses.

The discrepancy has a substantive explanation. Losses are determined mainly by two components of the indicator, the probability component and the severity component. The regularity, detection and resilience components affect

losses indirectly or do not affect mean losses at all. Thus, online monitoring sharply increases the detection component but changes mean losses little if most failures arise from causes that monitoring does not influence. Conversely, measures that reduce waiting at the border can substantially reduce losses while changing the indicator comparatively little.

This leads to a conclusion about how the two characteristics relate. Expected losses answer the question of how much the chain costs the cargo owner on average. The composite indicator answers a broader question: how well the chain can preserve the cargo under different conditions, how evenly failures are distributed over time and whether the chain can notice a problem in time. For a cargo owner with valuable but time-insensitive goods, the second question may matter more than the first, because the owner's contractual obligations to buyers depend on the predictability of deliveries. Both characteristics are therefore best used together, as is done in the measure selection model (Section 8.7).

Conclusions to Chapter 2

Research on supply chain reliability has developed in four streams: transfer of classical reliability theory, risk management, the resilience concept and the reliability of transport systems. Each of them touches on cargo integrity, but none treats it as a separate dimension of reliability.

It is proposed to distinguish between cargo preservation as an activity, integrity as a state, loss of integrity as an event and integrity-oriented supply chain reliability as a property of the system. Cargo securing is a preservation measure and affects integrity reliability through the probability of mechanical damage during the driving stages.

Common performance indicators such as OTIF, SCOR perfect order fulfilment and the damage claims ratio are binary, are measured at the moment of delivery and do not reflect the severity, frequency and location of failures, the chain's ability to limit their consequences or its sensitivity to disruptions. A hypothetical example showed that, with the same value of the perfect order metric, the losses of two chains can differ almost tenfold.

The concept of an integrity failure tied to each act of handover has been introduced, together with a classification of failures into total, partial quantitative, qualitative apparent, qualitative hidden and pre-failure states. The distinction between evident and hidden failures is consistent with Article 30 of the CMR. Analysis of documentation showed that the documents needed to calculate all reliability

components already exist in practice but belong to different chain participants. Assessing reliability requires not new documentation but exchange of existing data linked to the consignment. Only two documents are missing: the securing calculation sheet and the en-route securing inspection report, which are both evidence of proper securing and a source of data on pre-failure states.

Comparison of the indicator with expected losses revealed a strong but not functional relationship between them, so the indicator is not replaced by mean losses but complements them with characteristics of regularity, detection and resilience.

CHAPTER 3.

DYNAMIC LOADS ON CARGO AND THE CAUSES OF CARGO SHIFTING

3.1. Hazardous driving situations: braking, manoeuvring and road surface

Cargo securing can be designed correctly only if it is known when and why the cargo tends to move. The analysis therefore begins by identifying hazardous situations, i.e. driving modes in which the cargo is subject to inertial forces capable of overcoming friction and the restraining forces of lashings. These situations fall into three groups according to the source of acceleration: braking, manoeuvring and the effect of road surface irregularities.

Braking. This type of load is the most thoroughly standardised. EN 12195-1 adopts an acceleration coefficient $c_x = 0{,}8$, or about 7,85 m/s^2, for calculating securing in the forward longitudinal direction [21].

Two modes should be distinguished. Service braking with an acceleration of 0,2–0,5 g is repeated dozens of times per journey. Each such braking event is not dangerous on its own, but together they create cyclic loading under which lashings gradually stretch and their tension weakens. Emergency braking with an acceleration of about 0,8 g is a single event, and it is the event for which securing is designed.

Field measurements show that the standard value is not an absolute limit. A. Zuska, D. Kurczyński and J. Jackowski carried out road braking tests of a category N1 van and a category N3 tractor-semitrailer on dry and wet asphalt and concrete. For the heavy vehicle, the coefficient c_x did not exceed 0.8. For the van it exceeded 0,8, and the highest deceleration was 9,52 m/s^2 [86]. The longitudinal load is also affected by cargo placement. T. Skrúcaný, J. Vrábel and P. Kazimír showed that the braking characteristics of a light commercial vehicle depend more on where along the platform a heavy load is placed than on its mass [65].

The forces acting on the cargo during emergency braking are shown in Fig. 3.1. The inertial force F_{in} acts at the centre of mass of the cargo and is directed forward. It is opposed by the friction force F_{fr} between the cargo and the deck and by the restraining forces of the lashings. Gravity G and the deck reaction N act vertically.

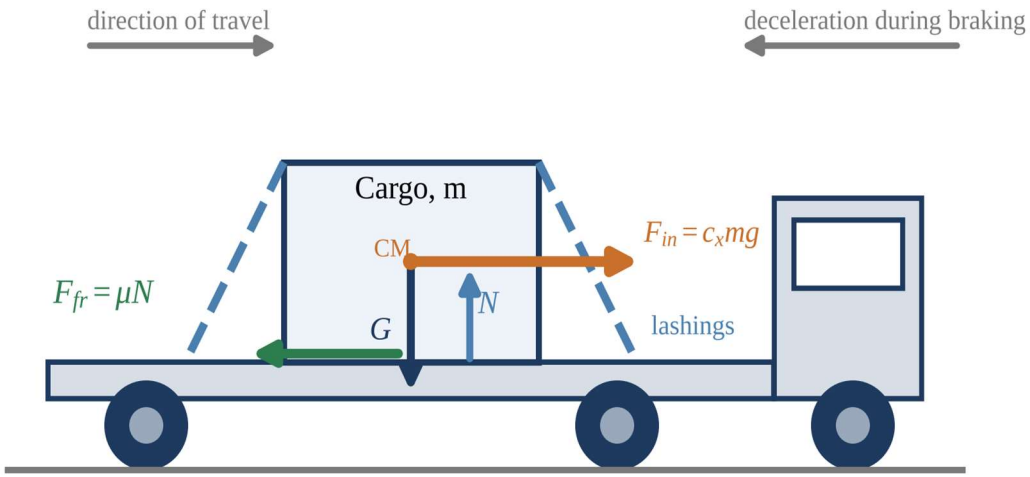


Fig. 3.1. **Forces acting on the cargo during emergency braking**
Source: developed by the authors

Manoeuvring. When the vehicle travels along a curve, the cargo is subject to a transverse force proportional to the centripetal acceleration:

$$a_y = \frac{v^2}{R}, \tag{3.1}$$

where v is the vehicle speed, m/s;

R is the curve radius, m.

At a speed of 60 km/h (16,7 m/s) on a curve with a radius of 50 m, the transverse acceleration is 5,56 m/s^2, or 0,57 g. This already exceeds the standard value of 0,5 g. A situation that is common in non-urban traffic, with moderately excessive speed on an exit ramp or in a bend, thus creates a load for which the standard calculation is not designed. Even more dangerous are sudden obstacle-avoidance manoeuvres and trailer sway, when the instantaneous transverse acceleration briefly increases.

Measurements on real routes give an idea of how often such events occur. J. Jagelčák and J. Kubáňová recorded semi-trailer accelerations on motorways and roads of other categories. The highest braking deceleration was about 0,49 g and the highest transverse acceleration about 0,33 g. Most events fell within the 0,1–0,2 g range. Events with accelerations above 0,3 g occurred about 0,1 times per 1000 km on motorways and about 1,4 times per 1000 km on other roads [33]. It

follows that the road category determines the frequency of hazardous episodes more than their maximum magnitude.

Road surface. Irregularities, potholes, railway crossings and speed bumps produce vertical shocks. During a shock, the force pressing the cargo onto the deck briefly decreases, and the friction force decreases with it. M. Vlkovský and co-authors, having measured the accelerations of a Tatra truck on roads of different quality, found that the standard limits were exceeded on the vertical axis in 75 % of cases and on the transverse axis in 56,3 % of cases [79]. Statistical modelling of accelerations for different surface types, carried out by J. Neubauer, M. Vlkovský and J. Michálek, confirmed that the type and condition of the surface substantially change the distribution of loads on the cargo [51]. Inexpensive MEMS sensors are increasingly used for measurements of this kind. Their suitability for assessing cargo dynamics on road vehicles was demonstrated by J. Gnap and co-authors [25]. The main types of hazardous situations are systematised in Table 3.1.

Table 3.1 **Types of hazardous situations during cargo transport**

№	Situation	Load direction	Nature of action	Approximate acceleration level
1	Service braking	Longitudinal (forward)	Cyclic, repeated	0,2–0,5 g
2	Emergency braking	Longitudinal (forward)	Single impulse	up to 0,8 g; higher for N1 vans
3	Sharp acceleration	Longitudinal (backward)	Single	up to 0,5 g
4	Cornering	Transverse	Sustained (seconds)	0,2–0,6 g depending on speed and radius
5	Obstacle avoidance, trailer sway	Transverse, alternating	Short, repeated	briefly above 0,5 g
6	Driving over potholes and irregularities	Vertical	Impact, systematic	briefly above 1 g
7	Combined braking and manoeuvre	Longitudinal and transverse simultaneously	Single	resultant up to 0,9 g
8	Collision	Any	Accidental	far exceeds the standard values

Source: compiled by the authors using [21, 33, 79, 86]

This issue is particularly important for Ukrainian roads. A large part of the network has had a damaged surface since 2022, so vertical shocks occur here systematically. The danger is aggravated by the superposition of loads: braking, cornering and a shock from an irregularity may act simultaneously, and their combined effect is greater than that of each separately.

Situations 1–7 are covered by the securing calculation; situation 8 lies outside it. Two circumstances matter most in practice. Cyclic loading (situations 1 and 6) is underestimated, although it is precisely this loading that gradually loosens lashings without any external signs. Combined loading (situation 7) is not covered by the standard axis-by-axis calculation.

3.2. Cargo stability model

Let us consider the cargo as a rigid body on a horizontal deck. Its state is determined by two possible modes of losing equilibrium: sliding along the deck and tipping about a lower edge.

Static equilibrium. On a stationary vehicle, the cargo is subject only to gravity and the deck reaction. Sliding is impossible, and tipping on a horizontal deck is also impossible if the centre of mass is above the support area. The tipping stability of the cargo is 46haracterized by the ratio

$$K_{st} = \frac{b}{2h_c}, \tag{3.2}$$

where b is the width (or length) of the cargo base in the direction of possible tipping, m;

h_c is the height of the centre of mass above the deck, m.

Dynamic loading. A horizontal acceleration $c \cdot g$ produces a tipping moment $c \cdot mg \cdot h_c$. It is opposed by the moment of gravity $mg \cdot b/2$. An unsecured load therefore does not tip provided that

$$K_{st} = \frac{b}{2h_c} > c. \tag{3.3}$$

This condition refines the common simplified interpretation according to which a load is considered unstable only when $K_{st} < 1$. In the transverse direction, where the standard coefficient is 0,5–0,6, a load with the ratio $K_{st} = 0{,}55$ formally

stands securely but will tip over without securing when cornering. For example, a pallet 1,2 m wide with its centre of mass at a height of 1,1 m has $K_{st} = 0{,}55$ and is at the limit of stability in the transverse direction.

Sliding does not occur if the inertial force does not exceed the friction force:

$$c \cdot mg \leq \mu \cdot mg, \text{ that is, } c \leq \mu. \tag{3.4}$$

Since real values of μ lie between 0,1 and 0,6, while the standard coefficient for the forward direction is 0,8, an unsecured load is never held in the longitudinal direction by friction alone. In the transverse direction, friction can be sufficient only on anti-slip mats.

Three characteristic states of the cargo are shown in Fig. 3.2: static equilibrium, the critical state under an inertial force without securing, and equilibrium restored by the securing system.

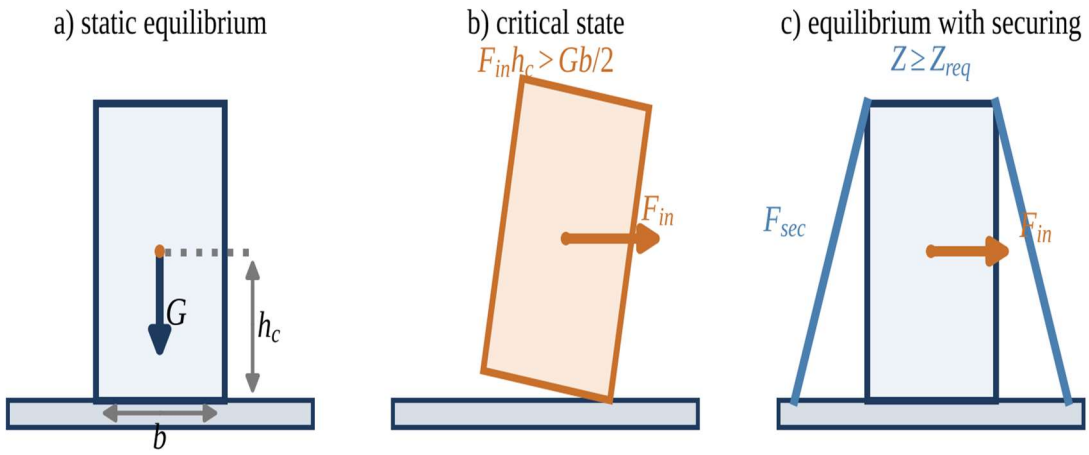


Fig. 3.2. **States of the cargo: a) static equilibrium; b) critical state under an inertial force; c) equilibrium provided by the securing system**
Source: developed by the authors

Combined loading. The standard procedure checks securing separately for each direction. In a real situation, however, for example when braking while avoiding an obstacle, the longitudinal F_x and transverse F_y inertial forces act together. Their resultant is directed at an angle to the vehicle axis and is greater in magnitude than either component. The friction force, in turn, can resist displacement in any direction, but its magnitude does not exceed μN. The condition of no sliding under combined loading therefore takes the form

$$\sqrt{F_x^2 + F_y^2} \leq F_{fr} + F_{sec}, \tag{3.5}$$

where F_{fr} is the friction force, N;

F_{sec} is the restraining force of the lashings in the direction of the resultant force, N.

Condition (3.5) is stricter than the axis-by-axis check. If the securing barely satisfies the condition for the forward direction, any simultaneous transverse acceleration upsets the equilibrium.

The axis-by-axis calculation is methodologically incorrect for combined loading scenarios and systematically underestimates the required number of lashings. The method set out in Chapter 4 is based on this proposition.

3.3. Inertial forces and friction

The inertial forces acting on a load of mass m in three directions are determined as

$$F_x = c_x mg, \quad F_y = c_y mg, \quad F_z = c_z mg, \tag{3.6}$$

where c_x, c_y, c_z are the acceleration coefficients in the longitudinal, transverse and vertical directions;

g is the acceleration due to gravity, 9,81 m/s^2.

For a load of 5 000 kg during emergency braking ($c_x = 0{,}8$), the longitudinal inertial force is $0{,}8 \cdot 5000 \cdot 9{,}81 = 39\,240$ N, or about 39,2 kN. In the transverse direction ($c_y = 0{,}5$), it equals 24,5 kN.

The friction force between the cargo and the deck is given by Coulomb's law:

$$F_{fr} = \mu \cdot N = \mu \cdot mg, \tag{3.7}$$

where μ is the friction coefficient between the cargo and the deck;

N is the normal force with which the cargo presses on the deck, N.

The part of the inertial force that is not compensated by friction and must be taken up by the lashings will be called the residual load:

$$F_{res} = mg(c - \mu), \quad F_{res} \geq 0. \tag{3.8}$$

Formula (3.8) shows how strongly the need for lashings depends on the friction coefficient (Fig. 3.3). For a load of 5 000 kg in the forward direction, the residual load at $\mu = 0{,}2$ is 29,4 kN, and at $\mu = 0{,}6$ only 9,8 kN, i.e. three times less. In the transverse direction at $\mu \geq 0{,}5$, the residual load is zero, and friction alone holds the cargo against sliding (but not against tipping, which is checked by condition (3.3).

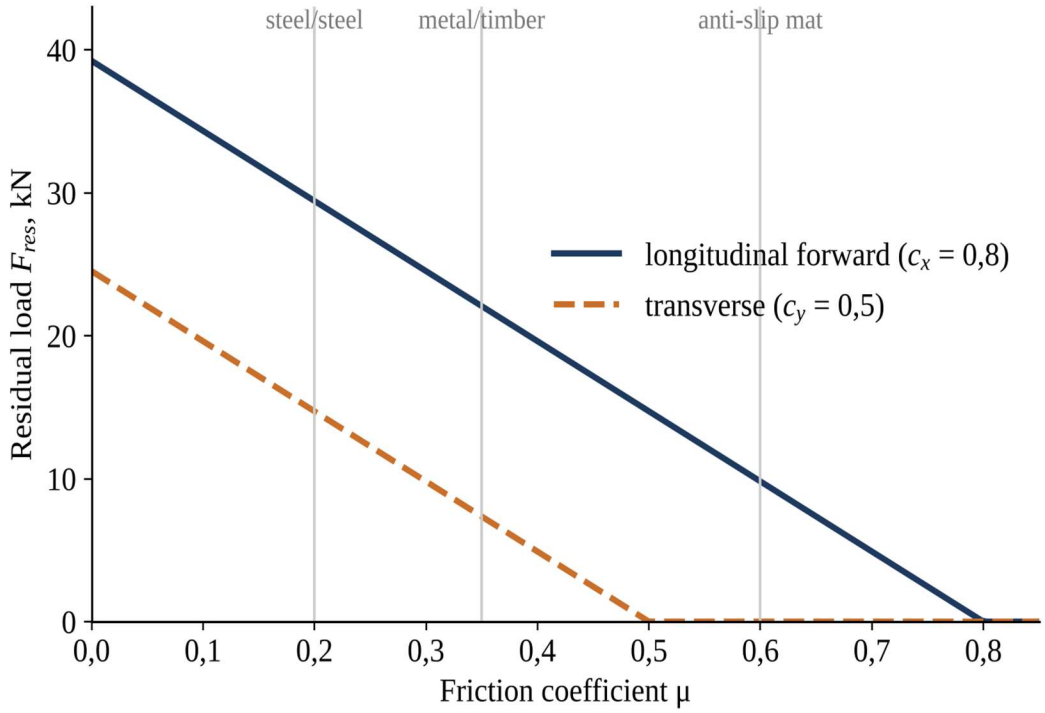


Fig. 3.3. **Residual load on the lashings as a function of the friction coefficient (load mass 5 000 kg)**

Source: developed by the authors

The effect of friction is especially pronounced with top-over lashing, when the lashings pass over the top of the cargo. Such a lashing does not hold the cargo directly but increases the pressing force by $2F_T \sin\alpha$, where F_T is the pretension of the lashing and α is the angle between the lashing and the deck. Disregarding the safety factors provided by the standard, the minimum number of top-over lashings is.

$$n \geq \frac{mg(c-\mu)}{2\mu F_T \sin} \tag{3.9}$$

The calculation by formula (3.9) for the same 5 000 kg load (forward direction, lashing pretension 4 kN, angle 80°) is given in Table 3.2.

Moving from a smooth surface with $\mu = 0{,}2$ to an anti-slip mat with $\mu = 0{,}6$ reduces the number of top-over lashings from 19 to 3. Increasing friction is therefore the cheapest way to reduce the need for lashings. In practice, nobody fits 19 lashings to a 5 t load, and with low friction the carrier switches to direct lashing or blocking. Yet it is precisely with low friction that cargo is most often secured with a few top-over lashings "as usual".

Table 3.2 **Required number of top-over lashings as a function of the friction coefficient (m = 5 000 kg, F_T = 4 kN, α = 80°)**

Friction coefficient μ	Forward residual load, kN	Pressing contribution of one lashing, kN	Required number of lashings
0,2	29,4	1,58	19
0,3	24,5	2,36	11
0,4	19,6	3,15	7
0,5	14,7	3,94	4
0,6	9,8	4,73	3

Source: calculated by the authors

Friction coefficient values depend on the pair of materials and the condition of the surfaces. EN 12195-1 gives values for typical material combinations and requires that the calculation use either these values or values confirmed by testing [21]. Generalised indicative ranges are given in Table 3.3.

Table 3.3 **Indicative ranges of the friction coefficient for typical surface pairs (dry, clean surface)**

№	Cargo surface	Deck surface	Indicative range of μ	Note
1	Steel (smooth)	Steel (smooth)	0,10–0,20	Mechanical restraint required
2	Metal	Wood, plywood	0,20–0,35	Depends on surface finish
3	Sawn timber	Sawn timber, plywood	0,35–0,45	Planed timber has lower values
4	Plastic pallet	Wood, metal	0,10–0,20	Mats or blocking required
5	Any	Rubber anti-slip mat	about 0,6	Provided surfaces are clean and dry
6	Any	Wet, snow-covered or oily	well below the tabulated values	See the effective coefficient (Chapter 4)

Source: compiled by the authors on the basis of [18, 21].

Calculations use the values given in the standard or confirmed by testing.

3.4. Causes and consequences of cargo shifting

Cargo shifting results from specific causes that can be identified and eliminated. Cause-and-effect analysis makes it possible to move from responding to incidents to managing risks. On the basis of the literature and typical incident scenarios, the causes of shifting are divided into six groups (Table 3.4).

The relationship between causes and consequences is shown in Fig. 3.4. Most of the causes are controllable, i.e. they depend on the decisions of the participants in the carriage. Even weather and road conditions, which the carrier

cannot influence, become controllable if they are taken into account in the calculation: reduced friction on a wet deck can be anticipated and compensated.

Table 3.4 **Groups of causes of cargo shifting and their consequences**

№	Cause	Group	Immediate consequence	Further consequences
1	Insufficient restraining capacity of the securing due to a calculation error or lack of calculation	Design	Cargo shifts or falls while driving	Crash, injury to third parties, property damage
2	Spontaneous loosening of lashings due to vibration and cyclic loading	Physical	Gradual displacement without signs noticeable to the driver	Late detection, loss of vehicle stability
3	Uneven mass distribution, incorrect stowage	Procedural	Axle overload, shift of the centre of mass	Impaired handling, rollover in a bend
4	Wear, damage or breakage of lashings	Technical	Sudden loss of securing at speed	Crash with serious consequences
5	Excessive speed in curves, sharp manoeuvres	Behavioural	Securing overloaded by transverse force	Vehicle rollover, road blockage
6	Securing method unsuited to cargo properties; moisture, ice or dirt on the deck	Environmental and design	Reduced friction, cargo damaged by lashings	Property losses of the cargo owner, civil liability

Source: developed by the authors

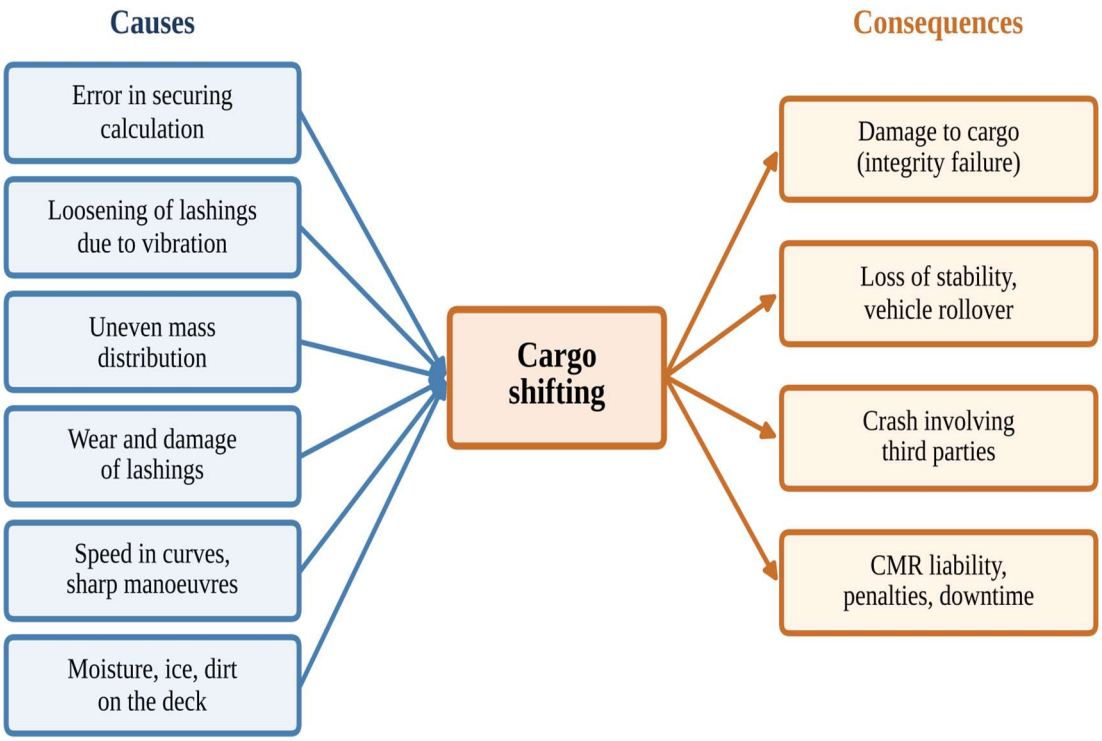


Fig. 3.4. **Cause-and-effect diagram of cargo shifting**
Source: developed by the authors

The consequences of shifting usually develop as a cascade. A small initial displacement changes the position of the centre of mass. The driver feels the change in vehicle behaviour and corrects the trajectory sharply. This creates a new wave of load on the securing, which is already partly loosened. The securing fails, the cargo moves or falls, and a crash occurs, often involving third parties. Risk is managed most effectively at the first link of this sequence, by preventing the initial displacement. At later stages, the driver's options are sharply limited. The consequences of shifting are best considered at three levels.

The physical level covers damage to the cargo, packaging and body. The road traffic level covers crashes, injuries and road closures. The legal and economic level covers CMR liability, administrative penalties, insurance payouts, vehicle downtime and loss of reputation. For the supply chain, cargo shifting is an integrity failure, mostly of the qualitative apparent type (see Table 2.4). If the cargo is destroyed, the failure is total, while damage to internal components discovered after delivery is a hidden failure.

3.5. Loss of lashing pretension during the journey

Section 3.1 noted that cyclic loading gradually loosens lashings. For top-over lashing this effect is particularly important, since the restraining force of such securing is directly proportional to the pretension. A direct lashing works differently: its capacity is determined by the lashing capacity rather than the pretension, so loosening shows up as slack that lets the cargo gain speed before the lashing tightens. Let us consider how the loss of pretension in top-over lashings changes the securing margin depending on the distance travelled and the road condition. The mechanism of loosening is known from practice. A textile web gradually elongates under load, the cargo settles onto the deck, pallets deform slightly, and vibration from surface irregularities gradually takes up the clearances. Tension falls fastest at the start of the journey, after which the process slows down. Such dynamics are conveniently described by an exponential relationship with a residual level:

$$T(s) = T_0[r_\infty + (1 - r_\infty)e^{-s/s_0}], \tag{3.10}$$

where T_0 is the initial lashing pretension, kN;

s is the distance travelled, km;

r_∞ is the fraction of tension retained after prolonged driving;

s_0 is the characteristic loosening distance, km.

The authors were unable to find openly available, statistically substantiated values of the parameters r_∞ and s_0 for different road types. The calculation therefore uses values that reflect the qualitative pattern: the worse the road, the faster and deeper the tension drops. For a good road, $r_\infty = 0{,}85$, $s_0 = 150$ km; for a fair road, $r_\infty = 0{,}78$, $s_0 = 100$ km; for a poor road, $r_\infty = 0{,}70$, $s_0 = 60$ km. These values are design assumptions and should be refined by measuring lashing tension on real journeys (Section 9.6). The change in tension of a lashing with an initial value of 4 kN is shown in Table 3.5.

Table 3.5 **Modelled change in top-over lashing tension with distance travelled, kN**

Road condition	0 km	25 km	50 km	80 km	120 km	200 km	300 km	500 km
Good	4,00	3,91	3,83	3,75	3,67	3,56	3,48	3,42
Fair	4,00	3,81	3,65	3,52	3,39	3,24	3,16	3,13
Poor	4,00	3,59	3,32	3,12	2,96	2,84	2,81	2,80

Source: calculated by the authors using formula (3.10)

To assess the consequences of loosening, we introduce the safety factor of top-over lashing in the longitudinal direction as the ratio of the total restraining force to the inertial force:

$$K_{sf}(s) = \frac{\mu mg + 2n\mu T(s)\sin\alpha}{c_x mg}. \quad (3.11)$$

Consider a 5 000 kg load on a timber deck ($\mu = 0{,}4$), secured by top-over lashings at an angle of 80° with an initial pretension of 4 kN. By formula (3.9), the minimum number of lashings for this load is seven (Table 3.2). The calculation of K_{sf} for seven, eight and nine lashings is given in Table 3.6 and Fig. 3.5.

Table 3.6 **Safety factor of top-over lashing as a function of distance (m = 5 000 kg, μ = 0,4, T_0 = 4 kN, α = 80°)**

Number of lashings, road condition	0 km	50 km	80 km	120 km	200 km	500 km	Distance at which K_{sf} < 1, km
7, good	1,062	1,038	1,027	1,016	1,000	0,981	201
7, fair	1,062	1,014	0,994	0,976	0,955	0,939	70
7, poor	1,062	0,967	0,938	0,916	0,900	0,894	28
8, poor	1,142	1,034	1,001	0,976	0,957	0,950	81
9, poor	1,223	1,100	1,063	1,035	1,014	1,006	not reached

Source: calculated by the authors

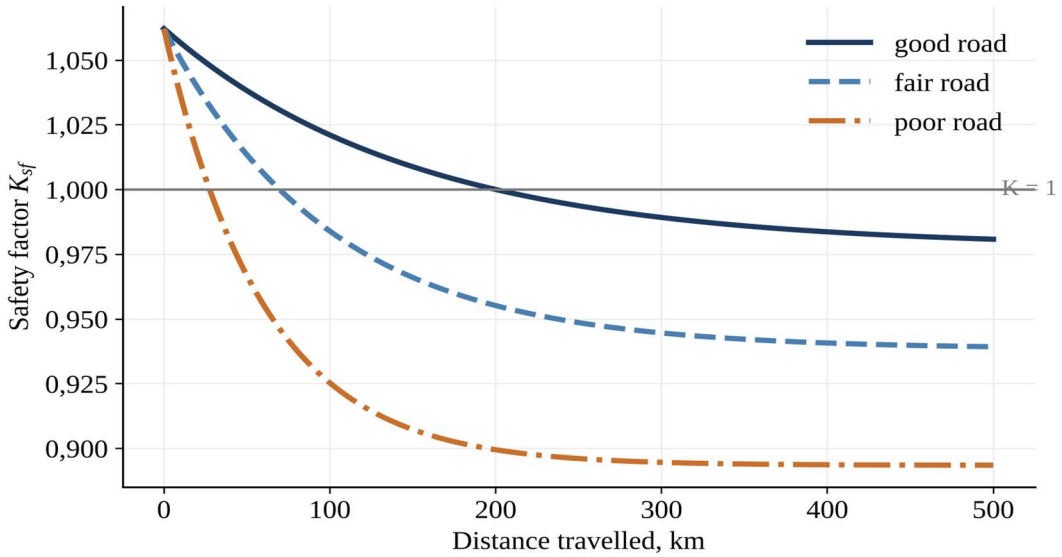


Fig. 3.5. **Change in the safety factor of top-over lashing while driving (seven lashings)**
Source: developed by the authors

The results show the following. Securing calculated with no margin on the basis of the initial pretension (seven lashings) loses its margin after only 28 km on a poor road. On a fair road this happens after about 70 km, and on a good road after about 200 km. It is thus in the first part of the journey that tension falls fastest, and a check of the securing after the first few dozen kilometres has a physical justification. This recommendation has long been present in practical guidelines [18].

The model gives it a quantitative explanation and shows that on poor roads the first check should be carried out earlier than on good ones. An additional lashing changes the picture substantially. With eight lashings, the securing on a poor road keeps its margin up to 81 km, and with nine the margin never disappears. A calculation based on the initial pretension should therefore be supplemented by a margin that compensates for the expected loosening. In the improved method, this function is performed by the required stability margin $Z_{req} = 1{,}25$ and the reserve lashing (Section 4.2).

Three rules for practice follow from this analysis. First, the first check of the securing should be carried out after 25–30 km on poor roads and after 50–80 km on good roads. Second, after each check the lashings are retensioned to the initial value, which returns K_{sf} to its original level. Third, top-over lashing calculated

without a margin is unacceptable on poor roads even with regular checks, because the margin can be lost between checks.

3.6. Tipping stability of typical loads

Condition (3.3) shows that an unsecured load does not tip if the ratio $b/(2h_c)$ exceeds the standard acceleration coefficient. For the transverse direction, this coefficient is 0,5, and for loads liable to tipping, 0,6 [21]. Let us consider which typical loads satisfy this condition (Table 3.7). For homogeneous loads, the centre of mass is assumed to be at mid-height.

The table shows that the tendency to tip depends on the orientation of the load unit. The same Euro pallet with a high stack is stable if it stands on the platform with its wide side (1,2 m) across the body, and unstable if it stands with its narrow side (0,8 m). In practice, pallet orientation is chosen to fill the body as densely as possible, and tipping stability is not considered. Yet the choice of orientation is the cheapest way to make a load stable without additional securing.

Table 3.7 **Transverse tipping stability of typical load units**

Load unit	Base width b, m	Height of centre of mass h_c, m	$b/(2h_c)$	Result for c_y = 0,5	Result for c_y = 0,6
Euro pallet, low stack (across the 1,2 m width)	1,20	0,75	0,800	Stable	Stable
Euro pallet, high stack (across the 1,2 m width)	1,20	1,10	0,545	Stable	Unstable
Euro pallet, low stack (across the 0,8 m width)	0,80	0,60	0,667	Stable	Stable
Euro pallet, high stack (across the 0,8 m width)	0,80	0,90	0,444	Unstable	Unstable
Equipment crate 1,0 × 1,8 m	1,00	0,90	0,556	Stable	Unstable
Cabinet or rack 0,8 × 2,4 m	0,80	1,20	0,333	Unstable	Unstable
Tall machine on a base frame	1,00	1,40	0,357	Unstable	Unstable

Source: calculated by the authors

For unstable loads, condition (4.3) becomes decisive, and the number of lashings is calculated from it. An example of such a calculation is given in Section 4.6. For loads at the limit of stability (values of $b/(2h_c)$ between 0,5 and 0,6), it is advisable to apply the coefficient 0,6, because on roads with a damaged surface transverse accelerations regularly exceed the standard values [79].

3.7. Load placement and axle load distribution

The placement of cargo on the platform affects not only how the lashings work but also how the vehicle behaves. T. Skrúcaný and co-authors showed that the braking characteristics of a light commercial vehicle depend more on the position of the load along the platform than on its mass [65]. For an articulated vehicle, load placement determines how the load is distributed between the tractor's fifth wheel coupling and the semi-trailer axle (axle group). This distribution affects the traction of the tractor's drive wheels, the stability of the combination during braking and compliance with permissible axle loads.

Consider a simplified static model of a 13,6 m semi-trailer. The kingpin is located 1,0 m from the headboard, and the centre of the axle group 10,3 m from it. A 20 t load is placed in different ways. The loads on the axle group R_a and on the kingpin R_k are found from the equilibrium equations:

$$R_a = G\,\frac{x_c - x_k}{x_a - x_k}, \quad R_k = G - R_a, \tag{3.12}$$

where G is the weight of the cargo, kN;

x_c, x_k, x_a are the distances from the headboard to the centre of mass of the cargo, the kingpin and the centre of the axle group, m.

The results for four placement options are given in Table 3.8. The semi-trailer's own mass is disregarded in order to show only the effect of cargo placement.

Table 3.8 **Distribution of the load from a 20 t cargo between the kingpin and the semi-trailer axle group**

Placement option	Position of the centre of mass from the headboard, m	Kingpin load, kN	Axle group load, kN	Share on the kingpin, %
Evenly over the full platform length	6,8	73,8	122,4	37,6
6 m block against the headboard	3,0	154,0	42,2	78,5
6 m block in the middle of the platform	6,8	73,8	122,4	37,6
6 m block at the rear doors	10,6	–6,3	202,5	–3,2

Source: calculated by the authors

The calculation reveals a conflict that is constantly encountered with part loads. From the securing point of view, it is most convenient to place the cargo tight against the headboard, which takes the longitudinal load during braking (Sections 4.5 and 4.7). For a heavy load occupying only part of the platform, however, such placement overloads the kingpin and the tractor's front axles, which carry almost 80 % of the cargo mass. Placement at the rear doors is even worse. The centre of mass ends up behind the axle group, and the kingpin load becomes negative, i.e. the cargo tends to lift the front of the semi-trailer. With such placement, the tractor loses traction during braking and the combination becomes uncontrollable.

The conflict is resolved by placing a heavy part load closer to the middle of the platform, so that the load distribution is close to that of even loading. The headboard then cannot serve as a stop, and longitudinal restraint has to be provided by other means: direct lashing, blocking beams or timber bracing to the headboard. These means must be taken into account in the calculation by formula (4.13). The choice of where to place the cargo and the choice of securing method are thus not two separate decisions but one, and the calculation sheet (Appendix A) must record both.

Conclusions to Chapter 3

Hazardous driving situations have been systematised into eight types according to the direction and nature of the load. The most underestimated proved to be the cyclic loading from service braking and surface irregularities, which gradually loosens lashings, and the combined loading from simultaneous braking and manoeuvring.

Published field measurements show that for category N1 vans the longitudinal deceleration can exceed the standard 0,8 g, and on roads with a poor surface vertical and transverse accelerations often go beyond the standard limits. Even a moderately excessive speed in a curve (60 km/h with a radius of 50 m) produces a transverse acceleration of 0,57 g, which is above the standard value.

The tipping stability condition has been refined: an unsecured load does not tip if $b/(2h_c)$ exceeds the standard acceleration coefficient. The simplified criterion $K_{st} < 1$ underestimates the danger for tall loads. Calculation for typical load units showed that the same Euro pallet with a high stack is stable when it stands with its wide side across the body and unstable in the opposite position, so the choice of orientation is the cheapest way to increase stability. The condition of no sliding under combined loading is stricter than the axis-by-axis check.

The friction coefficient proved to be the decisive securing parameter. For a 5 t load, moving from μ = 0,2 to μ = 0,6 reduces the residual longitudinal load threefold and the required number of top-over lashings from 19 to 3. A model assessment of pretension loss showed that top-over lashing calculated without a margin loses its margin after only 28 km on a poor road, whereas one or two additional lashings keep it over the whole route. This justifies the first check after 25–30 km on a poor road.

The causes of cargo shifting have been divided into six groups, most of which are controllable by the participants in the carriage. The consequences of shifting develop as a cascade, so risk management is most effective at the stage of preventing the initial displacement.

Calculation of the load distribution between the kingpin and the semi-trailer axles showed that for heavy part loads placement against the headboard overloads the kingpin, while placement at the rear doors unloads it; the placement and the securing method must therefore be chosen together.

CHAPTER 4.

AN IMPROVED METHOD FOR CALCULATING CARGO SECURING FORCES

The previous chapters established two prerequisites. Chapter 1 showed that Ukrainian regulation has no prescribed method for checking whether securing is sufficient, and that EN 12195-1 is the best-founded basis for such a method. Chapter 3 found that the standard calculation contains simplifications that, on roads with a degraded surface, can lead to underestimating the required number of lashings. The aim of this chapter is not to replace the standard but to supplement it with refinements that take real transport conditions into account. The result is an algorithm that combines a physically correct model with accessibility for engineers and dispatchers of road haulage companies.

4.1. Spatial force model and the concept of a critical loading scenario

4.1.1. Equilibrium equations in three dimensions

We consider the cargo as a perfectly rigid body with six degrees of freedom: three translational along the axes X, Y, Z and three rotational about them. Equilibrium of the cargo requires that six equations of statics be satisfied simultaneously:

$$\sum F_x = 0, \quad \sum F_y = 0, \quad \sum F_z = 0; \tag{4.1}$$

$$\sum M_x = 0, \quad \sum M_y = 0, \quad \sum M_z = 0. \tag{4.2}$$

Equations (4.2) describe what the standard procedure treats only as a separate check: even if translational movement of the cargo is blocked, it may still rotate about a lower edge, i.e. tip over. For the transverse direction, the condition of no tipping of a secured load takes the form

$$F_y h_c \le G\frac{b}{2} + \sum_j F_{sec,j}\ r_j, \tag{4.3}$$

where $G = mg$ is the weight of the cargo, N;

$F_{sec,j}$ is the force of the j-th lashing, N;

r_j is the lever arm of this force about the tipping edge, m.

For loads in which $b/(2h_c)$ is close to or below the standard acceleration coefficient (see condition (3.3)), it is condition (4.3), and not the no-sliding condition, that determines the required number of lashings. This explains cases in which a load that is adequately secured against sliding still tips over because no tipping check was performed.

4.1.2. Critical loading scenario and stability margin

The standard calculation considers each load direction separately. Real driving, however, is rarely “pure”. The driver brakes while avoiding a pothole or entering a bend, and it is such combinations that are most dangerous. To describe them, the concept of a critical loading scenario (CLS) is proposed. It is the combination of the longitudinal c_x and transverse c_y acceleration coefficients acting on the cargo simultaneously and the effective friction coefficient μ_{eff} at which the load on the securing system is greatest for a given route and cargo. The CLS does not necessarily coincide with the maximum value of an individual component. For a winter route with a poor surface, for example, it may be determined by moderate braking on a section with wet snow, where friction is minimal.

The reliability of the securing system in the CLS is measured by the stability margin:

$$Z = \frac{F_{fr}+F_{sec}}{\sqrt{F_x^2+F_y^2}} = \frac{\mu_{eff}mg+nF_e}{mg\sqrt{c_x^2+c_y^2}}, \quad (4.4)$$

where n is the number of lashings;

F_e is the effective restraining force of one lashing, taking into account the angle, wear and uneven pretension (see Section 4.2), N.

At $Z < 1$, the securing is insufficient and displacement in the CLS is inevitable. At $Z = 1$, the system is in a limit state. At $Z > 1$, the securing has a margin. The minimum permissible value consistent with the logic of the standard is one. For roads with a degraded surface, we propose a required margin of $Z_{req} \geq 1{,}25$. This value is justified by three circumstances. First, field measurements record accelerations above the standard values on poor roads [79]. Second, lashing tension decreases during prolonged driving with vibration. Third, some calculation parameters (the friction coefficient, the actual lashing angle) are known only approximately.

The CLS concept has a practical application. For typical routes and cargo categories, the CLS can be calculated in advance and specified in the company’s route documentation. The driver then knows which section of the route is critical and where an unscheduled securing check is needed. Current practice is different: securing is checked either on a schedule or only when a problem has already become noticeable.

4.2. Improving the method for determining the number of lashings

4.2.1. Factors that distort the standard calculation

The standard procedure is essentially a single step: the residual load is divided by the restraining capacity of one lashing and the result is rounded up. Under idealised conditions it is correct. In real transport, however, the result is affected by three further factors that it does not take into account.

Cyclic wear of lashings. A textile lashing that has been through several hundred tensioning and release cycles no longer has the nominal capacity shown on its label. The standard proceeds from nominal values. To take wear into account, we propose a cyclic wear coefficient:

$$k_c = 1 + \frac{N}{N_{max}}\,\delta_{max}, \tag{4.5}$$

where N is the number of completed use cycles of the lashing;

N_{max} is the service life of the lashing according to the manufacturer or the company's internal standard;

δ_{max} is the permissible relative reduction in capacity at the end of service life (assumed in the calculations to be 0,15 for textile webs and 0,10 for chains).

A lashing for which $N/N_{max} > 0{,}8$ should be withdrawn from service regardless of its outward condition. The value of δ_{max} is a design assumption of the authors and needs to be refined by testing for specific types of lashing equipment. Uneven pretension. It is practically impossible to achieve equal tension in all lashings of a set by hand. The actual restraining capacity of the system is therefore lower than the sum of the nominal values.

To take this factor into account, we introduce the non-uniformity coefficient $k_u = 0{,}85$, i.e. we assume that the effective capacity of the system is 85 % of the theoretical sum.

Change in securing geometry. Under the weight of the cargo and during driving, the lashing points and the cargo itself may shift, and the actual lashing angle differs from the planned one by several degrees. As shown in Section 4.3, the angle has a substantial effect on the effective horizontal component of the force.

The angle should therefore be determined from the actual position of the lashing points.

4.2.2. The improved formula

Taking these factors into account, the effective restraining force of one direct lashing in the horizontal plane is

$$F_e = \frac{LC \cdot \cos\alpha \cdot k_u}{k_c}, \tag{4.6}$$

where LC is the lashing capacity of the securing device, N;

α is the angle between the lashing and the horizontal plane.

The minimum number of lashings that ensures the required stability margin Z_{req} in the critical scenario is determined, taking formula (4.4) into account, as

$$n = \left\lceil \frac{\left(Z_{req}\sqrt{c_x^2 + c_y^2} - \mu_{eff}\right)mg}{F_e} \right\rceil + 1, \tag{4.7}$$

where the term "+1" corresponds to a reserve lashing that compensates for the possible failure of one of them during the journey.

The vertical component of the lashing force $LC\sin\alpha$ also presses the cargo down additionally and increases friction. It is not included in formula (4.6), which provides a certain margin.

For direct lashing at small angles this margin is insignificant; for steeply tensioned lashings it is larger (see Section 4.3). Formula (4.7) is more conservative than the standard procedure.

We consider this conservatism justified for conditions that combine roads with a damaged surface, seasonal reduction of friction and inadequate monitoring of lashing condition.

At the same time, under favourable conditions the difference between the methods is small (Chapter 5), so the refinements take effect mainly where they are really needed.

A comparison of the standard and improved methods is given in Table 4.1.

Table 4.1 **Comparison of the standard and improved securing calculation methods**

Parameter	Standard procedure	Improved method	Purpose of the refinement
Friction coefficient	Tabulated value for a dry surface	Effective coefficient μ_{eff} allowing for moisture, temperature and deck wear	Avoids overestimating friction under unfavourable conditions
Load direction	Separate check for each axis	Resultant force in the critical scenario	Accounts for combined loading
Sufficiency criterion	Equilibrium (Z = 1)	Required margin $Z_{req} \geq 1{,}25$	Compensates for uncertainty and loss of pretension
Condition of lashings	Nominal capacity	Cyclic wear coefficient k_c	Accounts for loss of capacity in service
Tension within a set	Sum of nominal forces	Non-uniformity coefficient $k_u = 0{,}85$	Accounts for manual tensioning
Reserve	Not provided	One reserve lashing	Maintains equilibrium if one element fails
En-route checks	Not regulated	Unscheduled check on CLS sections	Detects loosening before a critical state

Source: developed by the authors

4.3. Friction coefficient and lashing angle

4.3.1. Effective friction coefficient

EN 12195-1 gives values of the friction coefficient for dry, clean surfaces and warns that moisture, ice, dirt or oil reduce friction. It does not, however, establish a quantitative correction for these factors. We propose determining the effective friction coefficient as

$$\mu_{eff} = \mu_b \cdot k_w \cdot k_t \cdot k_f, \tag{4.8}$$

where μ_b is the base value of the friction coefficient for a dry surface (Table 3.3 or the standard);

k_w is the surface condition coefficient (1,0 – dry; 0,7 – damp or covered with wet snow; 0,4 – icy or oily);

k_t is the temperature coefficient for rubber and polymer surfaces (1,0 at $t > 0$ °C; 0,9 at t from –10 to 0 °C; 0,85 at $t < -10$ °C);

k_f is the deck condition coefficient (1,0 – new; 0,9 – fair; 0,75 – worn, with cracks and splinters).

The numerical values of the correction coefficients are design assumptions of the authors. They reflect the direction and order of magnitude of the effect of the corresponding factors and should be refined by friction measurements for specific surface pairs.

Consider an example. Metal products are carried on a timber deck in fair condition in winter, with wet snow on the surface and a temperature of –3 °C. Then $\mu_b = 0{,}30$, $k_w = 0{,}70$, $k_t = 0{,}90$, $k_f = 0{,}90$, and

$$\mu_{eff} = 0{,}30 \cdot 0{,}70 \cdot 0{,}90 \cdot 0{,}90 = 0{,}170. \tag{4.9}$$

The effective value is 43 % lower than the tabulated one. If the calculation uses the tabulated value, the contribution of friction is overestimated and the number of lashings underestimated.

This mechanism may explain some winter incidents in which the securing formally matched the calculation, but the calculation relied on a “summer” friction value.

4.3.2. Effect of the lashing angle

The angle α between the lashing and the horizontal plane determines what part of its force counteracts displacement. In practice, little attention is paid to this parameter: the lashing is tensioned however the position of the lashing points allows.

The force T in a direct lashing is resolved into a horizontal component $T\cos\alpha$, which directly counteracts displacement, and a vertical component $T\sin\alpha$, which presses the cargo onto the deck and increases friction. The total restraining effect is

$$F_{hold} = T\cos\alpha + \mu T\sin\alpha = T(\cos\alpha + \mu\sin\alpha). \qquad (4.10)$$

Setting the derivative of expression (4.10) with respect to α equal to zero gives the optimum angle:

$$\alpha_{opt} = \operatorname{arctg}\mu. \qquad (4.11)$$

At $\mu = 0{,}3$ the optimum angle is 16,7°, and at $\mu = 0{,}5$ it is 26,6°. With low friction, a direct lashing should therefore be as flat as possible. In practice, the angle is rarely less than 20–25°, because the lashing points are at floor level and the lashing has to be led over the cargo. The practical recommendation is therefore a range of 20–35°. Angles above 45° are undesirable, and at angles above 60° the horizontal component of the force becomes less than half the lashing capacity of the device ($\cos 60° = 0{,}5$). The dependence of the restraining effect on the angle for different friction values is shown in Fig. 4.1.

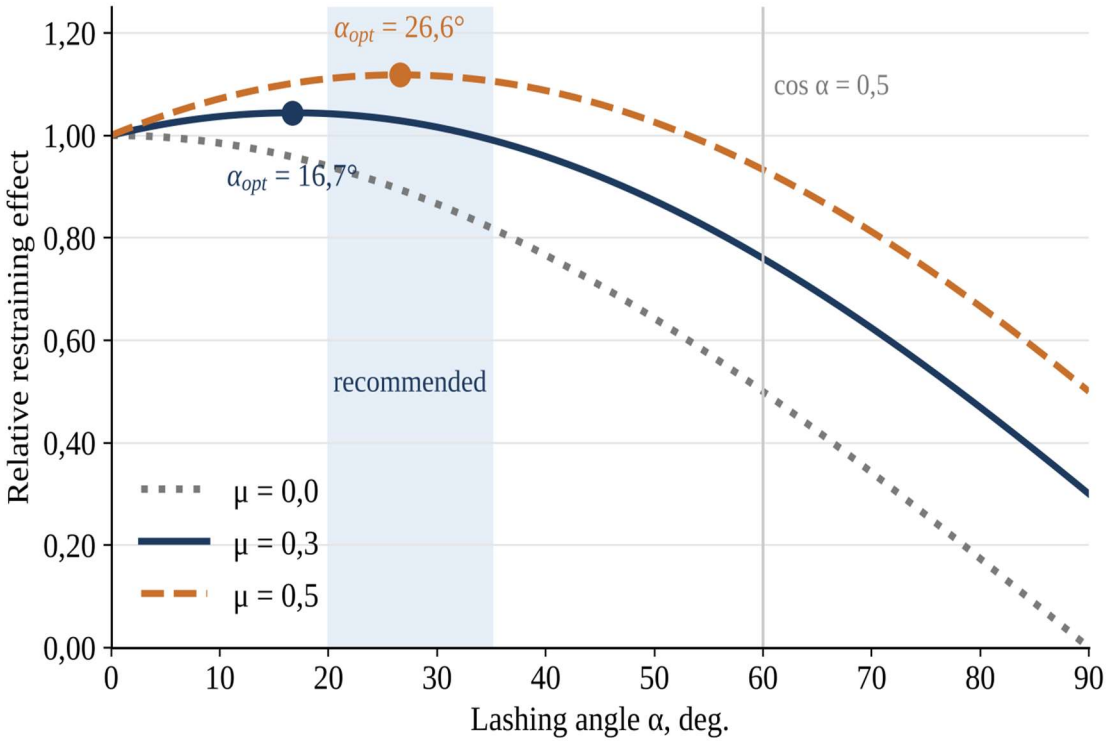


Fig. 4.1. **Relative restraining effect of a direct lashing as a function of the lashing angle**

Source: developed by the authors

The effect of the angle on the required number of lashings for a residual load of 40 kN, lashings with LC = 25 kN (2 500 daN) and a non-uniformity coefficient of 0,85 is given in Table 4.2.

As the angle increases from 15° to 65°, the horizontal component decreases by a factor of 2,3 and the required number of lashings rises from 2 to 5.

The relationship is non-linear and becomes steep beyond 45°. A well-planned layout of lashing points and a stowage pattern that give angles of 20–35° thus reduce the need for lashings without reducing safety.

Table 4.2 **Effect of the lashing angle on restraining capacity (F_{res} = 40 kN, LC = 25 kN, μ = 0,3)**

Angle α, deg.	cos α	Horizontal component, kN	Vertical component, kN	Restraining effect by (4.10), kN	Required number of lashings by horizontal component
15	0,966	24,15	6,47	26,09	2
25	0,906	22,66	10,57	25,83	3
35	0,819	20,48	14,34	24,78	3
45	0,707	17,68	17,68	22,98	3
55	0,574	14,34	20,48	20,48	4
65	0,423	10,57	22,66	17,36	5

Source: calculated by the authors

4.4. Algorithm of the improved calculation

The proposed refinements are combined in a step-by-step algorithm (Table 4.3).

It is presented in a form suitable for direct use by a company's technical staff, in particular for preparing calculation sheets for typical loads.

The algorithm differs from the standard procedure in three main respects. Using the effective friction coefficient (step 4) instead of the tabulated one makes it possible to take the real condition of the surfaces into account. Checking the stability margin against the resultant force (step 8) removes the systematic error of the axis-by-axis calculation. The reserve lashing (step 7) is an inexpensive measure that maintains equilibrium if one element fails.

The method has limitations that must be kept in mind. Model (4.4) treats the restraining force of the lashings as able to counteract the resultant force in any direction. This assumption corresponds to a direct lashing system in which lashings are placed on both sides and at both ends of the cargo. For other securing arrangements, the resultant force should be resolved along the lines of action of the specific lashings. The values of the correction coefficients k_w, k_t, k_f, δ_{max} and

k_u need experimental refinement. The corresponding research plan is given in Chapter 9.

Table 4.3 **Algorithm of the improved cargo securing calculation**

Step	Action	Formula or criterion	Note
1	Determine the cargo mass, base dimensions and height of the centre of mass	m, b, h_c	From cargo documentation or by weighing
2	Check tipping stability	$b/(2h_c) > c$ (3.3)	If not satisfied, check by (4.3) is mandatory
3	Determine the critical loading scenario for the route	c_x, c_y	For roads with a degraded surface, include a simultaneous transverse component
4	Calculate the effective friction coefficient	μ_{eff} by (4.8)	From the weather forecast and deck condition; at $\mu_{eff} < 0{,}25$ use anti-slip mats
5	Determine the lashing angle from the actual position of the lashing points	α	Recommended range 20–35°
6	Calculate the effective force of one lashing	F_e by (4.6)	Allowing for k_c and k_u
7	Calculate the number of lashings	n by (4.7)	Round up and add one reserve
8	Check the stability margin	$Z \geq Z_{req}$ by (4.4)	If not satisfied, increase n, increase friction or change the securing method

Source: developed by the authors

4.5. Blocking and combined securing arrangements

Formula (4.7) was derived for direct lashing, when the forces are taken up by lashings alone. In practice, cargo is often restrained by several mechanisms at once: friction, lashings and stops. The most common example is blocking the cargo against the headboard combined with top-over lashings that prevent lateral movement and bouncing. Let us consider how the calculation changes for such arrangements.

Blocking. A stop (headboard, sideboard, timber beam, wedge, special beam) takes a force equal to the residual load in the blocking direction minus the contribution of the other mechanisms. The required blocking force is

$$F_{bl} \geq (c - \mu_{eff})mg - nF_e, \tag{4.12}$$

where F_{bl} is the force the stop must withstand in the direction of the inertial force, N.

If there are no lashings in this direction ($n = 0$), the stop must take the entire residual load. For a 10 t load on a deck with $\mu_{eff} = 0{,}3$ in the forward direction, this is $(0{,}8 - 0{,}3) \cdot 98{,}1 = 49{,}1$ kN. Only a headboard whose strength has been confirmed for the corresponding load can withstand such a force. The strength of the headboard, sideboards and stanchions of the body must be known from the manufacturer's documentation. If it is not, blocking against the headboard cannot be relied on.

A feature of blocking is that a stop works in one direction only and only if it fits tightly. A gap between the cargo and the stop is dangerous: the cargo gains speed across the gap and strikes the stop with a force far greater than the static one. Securing guidelines therefore require gaps between the cargo and blocking elements to be minimal or filled [18].

Combined arrangement. If friction, lashings and a stop act together, the stability margin in the critical scenario is determined by a 72eneralization of formula (4.4):

$$Z = \frac{\mu_{eff}mg + nF_e + F_{bl}}{mg\sqrt{c_x^2 + c_y^2}}. \tag{4.13}$$

Here the direction of action of each mechanism must be taken into account. A stop against the headboard takes only the longitudinal component and contributes

nothing in the transverse direction. For combined arrangements, it is therefore advisable to resolve the resultant force into longitudinal and transverse components and check each, taking into account only the mechanisms acting in its direction, and then to check condition (4.13) separately for friction and for the devices that can resist a force in any direction. Choosing the arrangement. A summary of the calculations gives three practical guidelines:

– for heavy loads with low friction (metal on metal, plastic pallets), blocking is the most effective means of restraint in the longitudinal direction, and lashings are needed mainly for the transverse direction and against bouncing;

– for medium-weight loads on a timber deck with anti-slip mats, top-over lashing together with blocking against the headboard is usually sufficient without direct lashing;

– for loads with reliable lashing points (equipment, machinery, steel structures), direct lashing at shallow angles gives the greatest restraining force per lashing.

4.6. Worked examples of the algorithm

The application of the algorithm in Table 4.3 is shown in three examples. They differ in the type of cargo, the transport conditions and the mode of losing equilibrium that determines the number of lashings.

4.6.1. Steel coil, summer

Input data. A steel coil weighing 8 000 kg is carried in a cradle on a timber deck in fair condition. It is summer, the surface is dry, and the route runs mainly on highways. Direct lashings with LC = 25 kN are fitted at an angle of 30° and have used up half of their service life.

Steps 1–2. Weight $mg = 78{,}48$ kN. A coil in a cradle is not liable to tipping, so no check by (4.3) is needed.

Step 3. For a highway, the CLS is taken as $c_x = 0{,}8$, $c_y = 0{,}2$. Resultant inertial force $78{,}48 \cdot \sqrt{0{,}64 + 0{,}04} = 64{,}72$ kN.

Step 4. Base friction of metal on timber $\mu_b = 0{,}35$, dry surface $k_w = 1{,}0$, temperature above zero $k_t = 1{,}0$, deck in fair condition $k_f = 0{,}9$. Hence $\mu_{eff} = 0{,}315$, and the friction force is 24,72 kN.

Steps 5–6. Wear coefficient $k_c = 1 + 0{,}5 \cdot 0{,}15 = 1{,}075$. Effective force of one lashing $F_e = 25 \cdot 0{,}866 \cdot 0{,}85/1{,}075 = 17{,}12$ kN.

Step 7. The lashings must take $1{,}25 \cdot 64{,}72 - 24{,}72 = 56{,}17$ kN. Number of lashings $\lceil 56{,}17/17{,}12 \rceil + 1 = \lceil 3{,}28 \rceil + 1 = 5$.

Step 8. The stability margin with four design lashings is 1,44, and with the reserve lashing 1.71. The condition $Z \geq 1{,}25$ is satisfied.

4.6.2. The same coil in winter

Input data. The same, but the transport takes place in winter, with wet snow on the deck, a temperature of –3 °C and a route that includes sections of road with a damaged surface.

Step 3. For a route with poor sections, $c_y = 0{,}35$ is taken. Resultant inertial force $78{,}48 \cdot \sqrt{0{,}64 + 0{,}1225} = 68{,}53$ kN.

Step 4. $\mu_{eff} = 0{,}35 \cdot 0{,}7 \cdot 0{,}9 \cdot 0{,}9 = 0{,}198$, friction force 15,57 kN. Since $\mu_{eff} < 0{,}25$, the algorithm recommends anti-slip mats.

Step 7 without mats. Required force $1{,}25 \cdot 68{,}53 - 15{,}57 = 70{,}09$ kN. Number of lashings $\lceil 4{,}09 \rceil + 1 = 6$.

Step 7 with mats. For a rubber mat, $\mu_b = 0{,}6$ is taken, and the effect of moisture on the mat is weaker than on timber ($k_w = 0{,}85$). The deck under the mat does not affect friction ($k_f = 1{,}0$). Hence $\mu_{eff} = 0{,}6 \cdot 0{,}85 \cdot 0{,}9 = 0{,}459$, and the friction force is 36,02 kN. Required force $85{,}66 - 36{,}02 = 49{,}64$ kN, number of lashings $\lceil 2{,}90 \rceil + 1 = 4$.

Comparison of examples 4.6.1 and 4.6.2 shows the effect of the season: without mats, the same coil needs six lashings in winter instead of five. Anti-slip mats reduce the need to four, i.e. below the summer level without mats. This illustrates the conclusion of Chapter 3 that friction is the cheapest securing resource.

4.6.3. Tall equipment crate

Input data. A crate weighing 2 500 kg with a base of 1,0 × 1,2 m and a height of 2,2 m, centre of mass at 1,1 m. The crate stands with its narrower side (1,0 m) across the body, so the base width in the direction of possible tipping is 1,0 m. Top-over lashings over the crate, pretension 4 kN, angle 80°.

Step 2. $b/(2h_c) = 1{,}0/2{,}2 = 0{,}455$. This is less than the standard transverse coefficient, so the crate is unstable and the number of lashings is determined by the tipping condition.

Calculation by (4.3). For a load liable to tipping, $c_y = 0{,}6$ is taken. Weight 24,52 kN. Tipping moment $0{,}6 \cdot 24{,}52 \cdot 1{,}1 = 16{,}19$ kN·m. Restoring moment of gravity $24{,}52 \cdot 0{,}5 = 12{,}26$ kN·m. A top-over lashing passed over the top creates a restoring moment about the tipping edge approximately equal to $Tb\sin\alpha = 4 \cdot 1{,}0 \cdot 0{,}985 = 3{,}94$ kN·m. Equilibrium without a margin requires one lashing ($3{,}93/3{,}94 \approx 1{,}0$). With the required margin of 1,25, the tipping moment is 20,24 kN·m, the shortfall in restoring moment is 7,98 kN·m, and $\lceil 2{,}03 \rceil = 3$ lashings are needed.

Without a margin, the calculation therefore gives one lashing, which in practice means working at the limit of equilibrium. With the required margin and allowing for loss of pretension while driving (Section 3.5), three lashings are needed. If the crate is turned with its wider side (1,2 m) across the body, the ratio $b/(2h_c)$ rises to 0,545 and the need for securing against tipping decreases. A complete calculation sheet for one of the examples is given in Appendix A.

4.7. Vehicle body strength as a calculation constraint

A securing calculation makes sense only if the body can take the forces transmitted to it. Lashings are attached to lashing points and stops bear against the headboard and sideboards; if these elements are weaker than the forces, the securing fails together with them. The calculation by the algorithm in Table 4.3 must therefore be supplemented by a check of body strength.

Requirements for the strength of goods vehicle bodies are set by EN 12642. For bodies reinforced to Code XL, the headboard must withstand 50 % of the payload, the side walls 40 % and the rear wall 30 %.

Manufacturers' certificates usually stipulate conditions: the cargo is placed tightly from the headboard across the full width of the body, the gap to the rear doors does not exceed 15 cm, and the friction coefficient of the deck is not less than 0,3 [61]. If these conditions are not met, additional securing is required. A body without confirmed strength is regarded as one that only physically confines the cargo but does not take design forces.

Let us consider when a Code XL body can hold the cargo without additional securing. Suppose the semi-trailer has a payload of 24 t. The headboard then withstands $0{,}5 \cdot 24 \cdot 9{,}81 = 117{,}7$ kN, the side walls 94,2 kN and the rear wall 70,6 kN.

The residual load to be taken by the body depends, by formula (3.8), on the cargo mass and the friction coefficient. The results for a 20 t load are given in Table 4.4.

Table 4.4 **Residual load of a 20 t cargo compared with the strength of a Code XL body (payload 24 t), kN**

Friction coefficient	Forward (c_x = 0,8)	Headboard strength	Sideways (c_y = 0,5)	Side wall strength	Backward (0,5)	Rear wall strength
0,40	78,5	117,7	19,6	94,2	19,6	70,6
0,30	98,1	117,7	39,2	94,2	39,2	70,6
0,20	117,7	117,7	58,9	94,2	58,9	70,6
0,15	127,5	117,7	68,7	94,2	68,7	70,6

Source: calculated by the authors on the basis of the requirements for Code XL bodies [61]

With friction of 0,3 and above, a Code XL body takes the residual load in all directions with a margin, and tightly loaded cargo can be restrained by blocking. With friction of 0,2, the headboard works at the limit of its strength, with no margin at all.

With friction of 0,15, typical of a wet or icy deck, the forward residual load exceeds the strength of the headboard. In winter, even a certified body therefore does not remove the need for anti-slip mats or additional securing. This result is consistent with the manufacturers' condition of a minimum friction of 0,3: it is not a formality but follows directly from the calculation.

For bodies without enhanced strength, including most older curtainside semi-trailers, the side curtains and sideboards cannot be regarded as elements that take design forces. For such bodies, the number of lashings is determined by formula (4.7) without counting on blocking by the sideboards. The capacity of the lashing points must also be checked. It must be no less than the lashing capacity of the devices attached to them; otherwise the lashing point becomes the weakest link of the system.

The practical conclusion is that the body characteristics should be added to the input data of the calculation (step 1 of the algorithm in Table 4.3): whether there is a strength certificate, the body code and the capacity of the lashing points. These data should be entered in the calculation sheet (Appendix A).

4.8. Cargo securing in category N1 vans

EN 12195-1 was developed for goods vehicles, and its standard longitudinal acceleration coefficient of 0,8 corresponds to the braking capability of trucks. For light vans of category N1, this correspondence is not guaranteed. As noted in Section 3.1, the highest deceleration in road tests of a van reached 9,52 m/s^2 [86].

This corresponds to a coefficient of about 0,97, almost 20 % above the standard value. The authors of that study point out that EN 12195-1 covers trucks and does not take vans into account, although vans perform a large share of urban and regional deliveries.

Let us estimate how this difference affects the securing calculation. Consider loads of 800 and 1 200 kg in a van, secured by direct lashings with a lashing capacity of 4 kN (400 daN), which is typical of van lashing points.

The lashing angle is 30°, and the simultaneous transverse acceleration is 0.3. Two friction values are considered: 0,3 for cargo on a metal floor and 0,6 on an anti-slip mat. For each case, we determined the number of lashings designed for equilibrium ($Z = 1$) with the standard coefficient of 0,8 and the stability margin that this number of lashings actually provides if the real deceleration is 0.97.

The same was done for a calculation with the required margin of 1,25 (Table 4.5).

Table 4.5 **Effect of the higher deceleration of a van on the securing stability margin**

Cargo mass, kg	μ	Lashings for Z = 1 and c_x = 0,8	Actual Z at c_x = 0,97	Lashings for Z_{req} = 1,25 and c_x = 0,8	Actual Z at c_x = 0,97	Lashings required for Z_{req} = 1,25 and c_x = 0,97
800	0,3	2	1,03	3	1,40	3
800	0,6	1	0,96	2	1,33	2
1 200	0,3	3	1,03	4	1,28	4
1 200	0,6	2	1,08	2	1,08	3

Source: calculated by the authors

If the securing is designed only for equilibrium, the stability margin in a van with high deceleration falls to 0,96–1.08. In one of the four cases it is below one, i.e. the cargo shifts. The required margin of 1,25 absorbs the difference between the standard and actual deceleration in three cases out of four. In the fourth case (1 200 kg on a mat), the number of lashings for a margin of 1,25 coincides with that for equilibrium, and the actual margin is only 1.08. One more lashing is needed here.

For vans, it is advisable to apply a longitudinal coefficient of 1,0 instead of 0,8 or to block the cargo physically against the cab bulkhead, if its strength has been confirmed. The capacity of lashing points in vans requires particular attention. It is usually much lower than in trucks, and it is this capacity, rather than the lashings, that limits the restraining force.

Conclusions to Chapter 4

A spatial model of the forces acting on the cargo has been constructed that takes rotational as well as translational degrees of freedom into account. For loads in which $b/(2h_c)$ is close to the standard acceleration coefficient, the required number of lashings is determined by the no-tipping condition rather than the no-sliding condition.

The concepts of a critical loading scenario and of the stability margin of a securing system have been proposed; the margin compares the restraining forces with the resultant inertial force under simultaneous longitudinal and transverse accelerations. For roads with a degraded surface, a required margin of $Z_{req} \geq 1{,}25$ has been justified. The formula for determining the number of lashings has been improved by introducing a cyclic wear coefficient, a pretension non-uniformity coefficient and a reserve lashing, and the model of the effective friction coefficient takes into account the surface condition, temperature and deck wear. Under typical winter conditions, the effective friction value can be 43 % lower than the tabulated one.

The optimum angle of a direct lashing, $\alpha_{opt} = \text{arctg}\mu$, has been obtained, and it has been shown that increasing the angle from 15° to 65° reduces the horizontal component of the force by a factor of 2,3; a range of 20–35° is therefore recommended. The refinements have been combined in an eight-step algorithm suitable for preparing cargo calculation sheets at road haulage companies. The method has been extended to blocking and combined securing arrangements. Worked examples showed that the same steel coil needs six lashings in winter

instead of five in summer, and anti-slip mats reduce this need to four. For a tall equipment crate, the number of lashings is determined by the tipping condition: without the required margin the calculation gives only one lashing, with the margin three. A check of body strength showed that even a certified Code XL body holds a 20 t load by blocking with a margin only at friction above 0,2, so in winter it does not remove the need for anti-slip mats or additional securing.

For category N1 vans, whose braking deceleration can reach 0,97 g, securing designed only for equilibrium may prove insufficient; for them it is advisable to apply a longitudinal coefficient of 1,0 or to block the cargo against a bulkhead of confirmed strength.

CHAPTER 5.

COMPUTATIONAL VERIFICATION OF THE IMPROVED SECURING METHOD

The method proposed in Chapter 4 must be checked in two ways: whether it changes the calculation result where the standard procedure gives an error, and whether the additional costs it requires are justified. A field experiment simulating securing failure is technically complex and dangerous. The verification was therefore carried out as a computational experiment on model transport scenarios. This approach is common in transport engineering. Its limitation is that the results depend on the assumptions adopted, and all assumptions in this chapter are stated explicitly.The verification comprises four successive blocks: calculation of securing for six scenarios by the two methods, comparison of stability margins, assessment of the probability of shifting and of expected losses, and an economic assessment for a model company.

5.1. Conditions of the computational experiment

The scenarios were chosen to cover different physical properties of loads (mass, surface material, tendency to tip), different driving conditions (season, surface condition, route type) and different levels of risk. The scenario conditions are given in Table 5.1.

Table 5.1 **Conditions of the computational experiment (model scenarios)**

Scenario	Cargo and transport conditions	Mass, kg	Tabulated μ	μ_{eff}	Angle α, deg.	k_c	c_y in the CLS
S-1	Steel coils, summer, highway in fair condition	12 000	0,30	0,270	25	1,045	0,15
S-2	Sawn timber, winter, wet snow, road in poor condition	8 500	0,40	0,227	35	1,105	0,40
S-3	Paper reels, autumn, highway in good condition	6 000	0,40	0,400	20	1,030	0,15
S-4	Steel structures, winter, black ice	15 000	0,30	0,097	45	1,075	0,40
S-5	Palletised general cargo, autumn, urban route	4 200	0,35	0,220	30	1,060	0,45
S-6	Construction equipment, summer, unpaved road	9 800	0,35	0,262	40	1,090	0,35

Source: developed by the authors (scenario assumptions)

In all scenarios, the longitudinal acceleration coefficient of the CLS is taken at the standard value ($c_x = 0{,}8$), and the simultaneous transverse component c_y is set according to the route type. For direct lashing, textile lashings with LC = 25 kN were used.

Two calculations were performed for each scenario. The standard calculation reproduces common practice: the tabulated friction coefficient, a check in the longitudinal direction only and the horizontal component of the nominal lashing force without corrections.

The improved calculation was performed by the algorithm in Table 4.3 with the required margin $Z_{req} = 1{,}25$. For both securing variants, the stability margin was calculated by formula (4.4) under real conditions, i.e. with the effective friction coefficient, in the critical scenario and allowing for wear and uneven pretension. This reflects a situation in which the securing has been designed one way but works under real conditions.

5.1.1. Calculation for scenario S-2

As an example, consider scenario S-2: sawn timber weighing 8 500 kg, wood on wood, wet snow, –3 °C, deck in fair condition, lashing angle 35°, lashings that have used up 70 % of their service life.

Standard calculation. Weight of the cargo $mg = 83\,385$ N. With the tabulated $\mu = 0{,}40$, the friction force is 33 354 N, the longitudinal inertial force $0{,}8mg = 66\,708$ N and the residual load 33 354 N. The horizontal component of the force of one lashing is $25\,000 \cdot \cos 35° = 20\,479$ N. Hence $\lceil 33\,354/20\,479 \rceil = \lceil 1{,}63 \rceil = 2$ lashings are required.

Improved calculation. Effective friction coefficient $\mu_{eff} = 0{,}40 \cdot 0{,}70 \cdot 0{,}90 \cdot 0{,}90 = 0{,}227$, friction force 18 912 N. Cyclic wear coefficient $k_c = 1 + 0{,}70 \cdot 0{,}15 = 1{,}105$. Effective force of one lashing by (4.6):

$$F_e = \frac{25\,000 \cdot 0{,}819 \cdot 0{,}85}{1{,}105} = 15\,753 \text{ N}. \qquad (5.1)$$

The resultant inertial force in the CLS ($c_x = 0{,}8$, $c_y = 0{,}4$) equals $83\,385 \cdot \sqrt{0{,}64 + 0{,}16} = 74\,582$ N. For a margin of 1,25, the lashings must take $1{,}25 \cdot 74\,582 - 18\,912 = 74\,316$ N. Hence

$$n = \left\lceil \frac{74\,316}{15\,753} \right\rceil + 1 = \lceil 4{,}72 \rceil + 1 = 6. \quad (5.2)$$

The stability margin of the two lashings determined by the standard calculation under real conditions is

$$Z = \frac{18\,912 + 2 \cdot 15\,753}{74\,582} = 0{,}68. \quad (5.3)$$

Securing that is considered sufficient under the standard procedure holds only two thirds of the required force in the critical scenario. What makes this situation dangerous is precisely that it cannot be seen.

The driver believes the securing is correct, an inspection finds no violations, and the cargo shifts during the first sharp manoeuvre on a snow-covered section. In summer, the same cargo with the same securing will be delivered without problems, and the systematic nature of the error will go unnoticed.

5.2. Comparison of stability margins

The results of the calculations for all six scenarios are summarised in Table 5.2 and shown in Fig. 5.1.

Table 5.2 **Number of lashings and stability margin by the two methods**

Scenario	Standard method: number	Standard method: margin Z	Improved method: design number	Improved method: margin Z	Improved method with reserve: number	Improved method with reserve: margin Z
S-1	3	0,91	5	1,29	6	1,49
S-2	2	0,68	5	1,31	6	1,52
S-3	2	1,30	2	1,30	3	1,71
S-4	5	0,64	11	1,28	12	1,38
S-5	1	0,70	3	1,62	4	2,08
S-6	3	0,83	6	1,37	7	1,55

Source: calculated by the authors

The results support three observations.

First, in five of the six scenarios, securing determined by the standard procedure has a stability margin below one under real conditions. The lowest values were obtained for the winter scenarios S-2 (0,68) and S-4 (0,64) and for the urban route S-5 (0,70), where large transverse accelerations combine with the low friction of pallets. Even in the summer scenario S-1 the margin is 0.91.

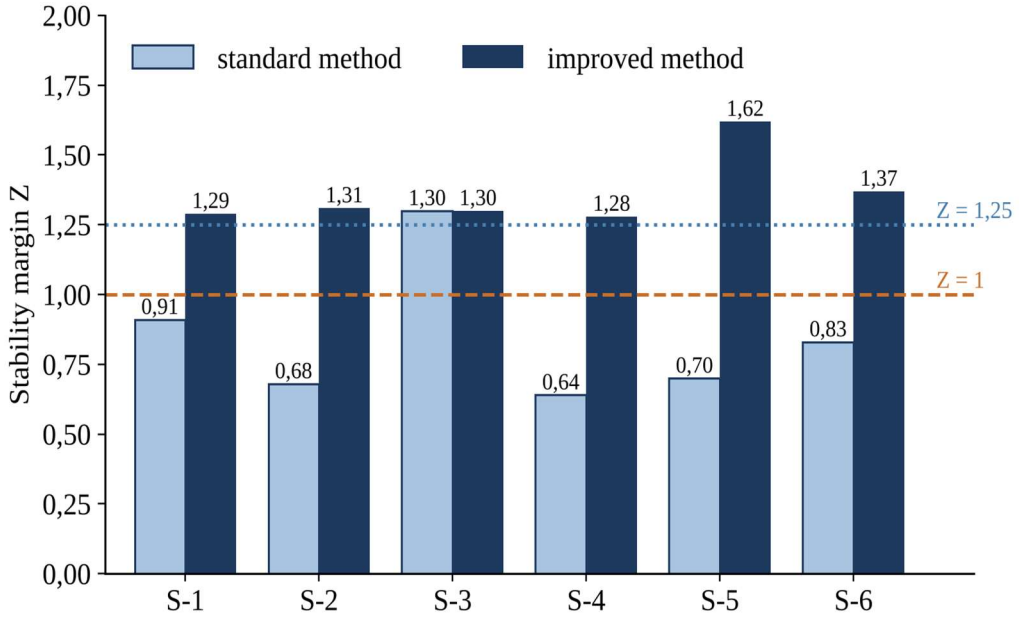


Fig. 5.1**. Stability margin of the securing system by the standard and improved methods**

Source: developed by the authors

The main cause here is the combined loading, which the axis-by-axis calculation does not cover, together with wear and uneven pretension of the lashings. Second, in scenario S-3 (paper reels on a dry deck, good road), both methods give the same design number of lashings, and the improved method adds only the reserve one. The method is therefore not excessively conservative. Under favourable conditions it hardly changes the result. Third, the greatest difference between the methods is observed in the highest-risk scenarios. For steel structures on black ice (S-4), the number of lashings rises from 5 to 12. The refinements take effect precisely where the error of the standard calculation is dangerous.

5.3. Probability of cargo shifting and expected losses

To move from the stability margin to risk, a model of the relationship between Z and the probability of shifting is needed. Open sources do not contain enough statistical data to estimate such a relationship. A model relationship was therefore used that reflects two physically obvious properties: at $Z = 1$ the probability of shifting in the CLS equals 0,5 (limit state), and as Z increases it falls rapidly. The logistic function has these properties:

$$P(\text{shift} \mid \text{CLS}) = \frac{1}{1+e^{k(Z-1)}}, \tag{5.4}$$

where the steepness parameter is taken as $k = 7$. With this value, the probability of shifting in the CLS is 0,80 at $Z = 0{,}8$, 0,15 at $Z = 1{,}25$ and 0,03 at $Z = 1{,}5$ (Fig. 5.2).

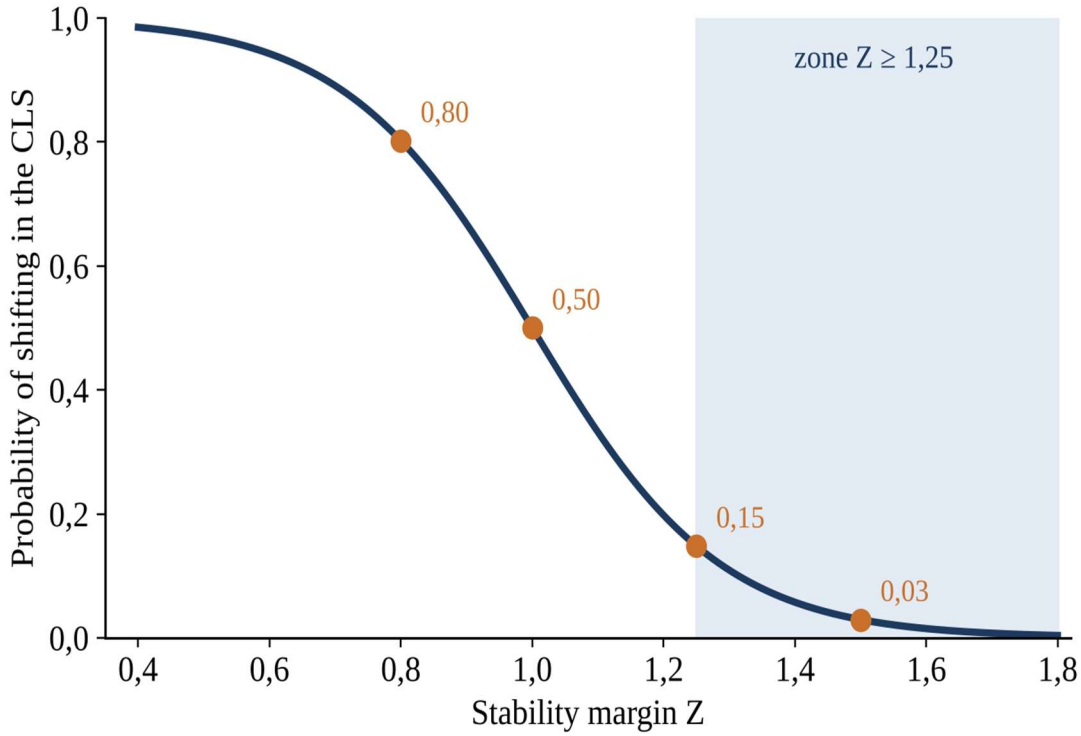


Fig. 5.2. **Model relationship between the probability of cargo shifting in the critical scenario and the stability margin**
Source: developed by the authors

The CLS does not occur on every journey. The probability of shifting per journey therefore equals the product of the probability of the CLS occurring, p_{CLS}, and the conditional probability (5.4). Values of p_{CLS} were taken from 0,004 for a highway in good condition to 0,015 for black ice. Expected losses per journey were calculated as the product of the probability of shifting and the average damage per incident, which covers the value of the damaged cargo, body repair, downtime and third-party liability. The results are given in Table 5.3. For the improved method, the probability was calculated for the design number of lashings without the reserve one, i.e. with some margin in hand.

Table 5.3 **Probability of cargo shifting per journey and expected losses (model estimate)**

Sc.	p_{CLS}	Probability of shifting (S), %	Probability of shifting (I), %	Reduction, %	Damage per incident, thousand UAH	Expected losses (S), thousand UAH	Expected losses (I), thousand UAH
S-1	0,005	0,327	0,057	82,6	900	2,95	0,51
S-2	0,012	1,087	0,123	88,7	450	4,89	0,55
S-3	0,004	0,043	0,043	0,0	520	0,23	0,23
S-4	0,015	1,389	0,189	86,4	1 000	13,89	1,89
S-5	0,010	0,891	0,013	98,5	380	3,39	0,05
S-6	0,010	0,761	0,071	90,7	650	4,95	0,46

Note: S – standard method, I – improved method. Source: calculated by the authors (the parameters p_{CLS}, k and the amount of damage are scenario assumptions)

For scenarios with a reduced margin, the improved method reduces the probability of shifting by 83–99 %. For steel structures on black ice (S-4), expected losses per journey fall from 13,89 to 1,89 thousand UAH, i.e. more than sevenfold. In scenario S-3, the risk is the same for both methods, which is consistent with the conclusions of Section 5.2. These results should be interpreted with their model nature in mind. The absolute values of probabilities and losses depend on the parameters k, p_{CLS} and the amount of damage, which were set on the basis of expert judgement. The relative result is much more robust: the direction and order

of magnitude of the risk reduction are determined by the difference in stability margin between the methods, not by these parameters.

5.4. Economic assessment of implementing the method

Scientific soundness and safety of the proposed solutions are necessary but not sufficient conditions for their implementation. Managers of transport companies make decisions by comparing costs with benefits. If the method is economically worthwhile, the company will have its own incentive to apply it, regardless of tighter enforcement.

5.4.1. Structure of losses from improper securing

Losses from cargo shifting consist of several items borne by different parties. The largest item is compensation for damaged cargo. Under the CMR, the carrier is liable for the integrity of the cargo from taking over to delivery, and an insurer that has compensated the cargo owner has a right of recourse.

The second item covers repair of the body and lashing equipment after an incident. The third relates to vehicle downtime due to detention during an inspection or dealing with the consequences of an incident. The fourth covers administrative penalties and third-party liability.

5.4.2. Calculation for a model company

We consider a model company that performs 1 000 journeys a year. The journeys are distributed among the scenarios as follows: S-1 and S-3 20 % each, S-2 and S-6 15 % each, S-5 20 %, S-4 10 %. The structure of losses is assumed to be: cargo 55 %, repairs 20 %, downtime 10 %, penalties and liability 15 %.

The additional costs of implementing the method comprise: running costs of additional lashings: 3 300 additional lashing uses per year at a unit cost of UAH 14 per use (depreciation of the lashing and the time to fit it), totalling UAH 46,2 thousand a year; anti-slip mats for 30 % of journeys at a unit cost of UAH 45 per journey, totalling UAH 13,5 thousand a year; one-off costs: staff training UAH 28,0 thousand and development of calculation sheets and a calculation tool UAH 12,0 thousand, totalling UAH 40,0 thousand. The results are given in Table 5.4.

Table 5.4 **Annual expected losses and costs of the model company (1 000 journeys a year), thousand UAH**

Item	Standard method	Improved method	Difference
Compensation for damaged cargo	2 298,4	274,2	–2 024,2
Repair of body and lashing equipment	835,8	99,7	–736,1
Vehicle downtime	417,9	49,9	–368,0
Penalties and third-party liability	626,8	74,8	–552,0
Total expected losses	4 179,0	498,5	–3 680,5
Additional lashings	–	46,2	+46,2
Anti-slip mats	–	13,5	+13,5
Net annual effect	–	–	3 620,8

Source: calculated by the authors (model estimate)

Under the assumptions adopted, the one-off costs of UAH 40 thousand pay back within a few days. This result is largely determined by the size of the expected losses, which depends on the model parameters of Section 5.3. It is therefore more important to assess how robust the conclusion about feasibility is to these parameters. Let f denote the factor by which the expected losses might have been overstated. With this correction, the net annual effect is $3\,680{,}5f - 59{,}7$ thousand UAH (Table 5.5).

Even if the expected losses are overstated twentyfold, the one-off costs pay back in less than four months. The method becomes loss-making only if the real losses from improper securing are 60 times smaller than the modelled ones. The conclusion about economic feasibility is therefore robust. It is explained by the fact that implementation costs are low, while the losses from a single serious cargo shifting incident are high.

Table 5.5 **Sensitivity of the economic effect to the size of expected losses**

Factor f	Reduction in expected losses, thousand UAH per year	Net annual effect, thousand UAH	Payback period of one-off costs
1,00	3 680,5	3 620,8	less than 1 week
0,20	736,1	676,4	about 3 weeks
0,10	368,1	308,4	about 1,6 months
0,05	184,0	124,3	about 3,9 months
0,016	59,7	0	break-even point

Source: calculated by the authors

The calculation has limitations. The real journey mix of a particular company will differ from the model one. Losses that are hard to quantify, such as reputational losses and those associated with deteriorating customer relations, were deliberately excluded, so this limitation understates the effect.

The model also does not take into account a possible reduction in insurance premiums for companies that document their use of the method.

5.5. Sensitivity of the method to design parameters

The improved method contains several parameters whose values were set on the basis of the authors' judgement without direct measurement: the pretension non-uniformity coefficient k_u, the permissible reduction in capacity δ_{max}, the required margin Z_{req} and the correction coefficients of effective friction. It is therefore necessary to check how far the calculation result depends on these values. If a small change in a parameter substantially changes the recommended number of lashings, the parameter needs priority experimental refinement. If not, inaccuracy in its value has practically no effect on the result. The quantity chosen for the analysis is the total number of lashings (including reserve ones) required for all six scenarios in Table 5.1.

Table 5.6 **Effect of design parameters on the required number of lashings**

Parameter variant	S-1	S-2	S-3	S-4	S-5	S-6	Total	Change relative to base, %
Base values	6	6	3	12	4	7	38	–
k_u = 0,75	7	7	4	14	4	8	44	+15,8
k_u = 0,95	6	6	3	11	3	6	35	–7,9
δ_{max} = 0,10	6	6	3	12	4	7	38	0,0
δ_{max} = 0,20	6	6	3	12	4	7	38	0,0
Z_{req} = 1,10	5	6	3	11	3	6	34	–10,5
Z_{req} = 1,40	7	7	4	14	4	8	44	+15,8
k_w 15 % lower	7	6	4	12	4	7	40	+5,3
k_w 15 % higher	6	6	3	12	4	7	38	0,0
LC = 20 kN	7	7	4	15	4	8	45	+18,4
LC = 50 kN	4	4	2	7	3	4	24	–36,8

Source: calculated by the authors

With the base parameter values, it is 38 lashings. For comparison, the standard axis-by-axis procedure gives 16 lashings for the same scenarios. Each parameter was varied separately, with the others kept at base values. The results are given in Table 5.6 and Fig. 5.3.

The analysis makes it possible to divide the parameters into three groups.

Parameters with a noticeable effect are the non-uniformity coefficient k_u and the required margin Z_{req}. Changing either of them within seemingly plausible limits changes the total requirement by 8–16 %. Both parameters reflect uncertainty rather than a physical quantity, so their values ultimately depend on what level of risk the company or the regulator considers acceptable. The value of $Z_{req} = 1{,}25$ is a compromise: increasing it to 1,40 adds six lashings for six journeys, while reducing it to 1,10 brings the margin down to a level that, as shown in Section 3.5, may disappear after a few dozen kilometres on a poor road.

Parameters with a weak effect are δ_{max} and the friction correction coefficients. Changing δ_{max} from 0,10 to 0,20 did not change the result in any scenario: the wear coefficient changes the effective lashing force by a few per cent, which is not enough to change the number of lashings after rounding. Reducing k_w

by 15 % added two lashings, while increasing it changed nothing. The method is thus robust to inaccuracy in these parameters. This does not mean, however, that they can be ignored. They matter in individual borderline cases where the design number is close to an integer

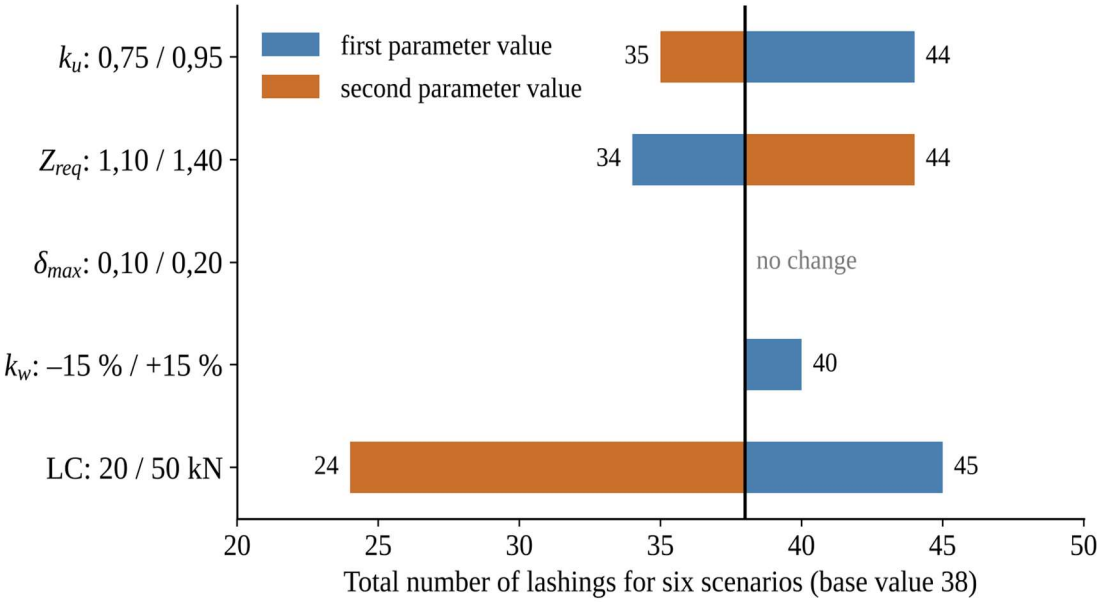


Fig. 5.3. **Change in the total number of lashings when the method parameters are varied**
Source: developed by the authors

The parameter with the strongest effect is a technical characteristic of the securing device, namely its lashing capacity *LC*. Moving from 2 500 daN webs to 5 000 daN webs reduces the total requirement by 37 %. For heavy loads (scenario S-4), the number of lashings falls from 12 to 7. For heavy loads with direct lashing, choosing higher-capacity equipment is therefore more economical than increasing the number of light lashings.

The difference between the standard procedure (16 lashings) and the improved method (38 lashings) seems large. It is, however, unevenly distributed. The largest share of the increase (7 of 22 lashings) falls on scenario S-4 (steel structures on black ice), where the standard procedure gives a stability margin of 0,64, i.e. the securing actually holds only two thirds of the required force. For scenario S-3 with favourable conditions, the increase is one lashing, and it is the reserve one. Six of the 22 additional lashings are reserves, one for each scenario.

The sensitivity analysis indicates the priorities for experimental research. The non-uniformity coefficient k_u needs the most refinement. It can be determined by a relatively simple experiment: measuring the tension of the lashings of one set tensioned by different operators. The parameter δ_{max} and the friction corrections have lower priority. The required margin Z_{req} is a matter not of measurement but of agreeing on an acceptable level of risk.

Conclusions to Chapter 5

The computational experiment on six model scenarios showed that securing determined by the standard axis-by-axis procedure with the tabulated friction coefficient has a stability margin below one under real conditions in five scenarios out of six. The lowest values were obtained for the winter scenarios (0,64–0,68) and the urban route (0,70).

The improved method ensures a stability margin of at least 1,25 in all scenarios. Under favourable conditions it does not change the design number of lashings, i.e. it is not excessively conservative, and the greatest difference between the methods occurs in the highest-risk scenarios. According to the model logistic relationship, the improved method reduces the probability of cargo shifting by 83–99 % in scenarios with a reduced margin, and for steel structures on black ice the expected losses per journey fall more than sevenfold.

For a model company with 1 000 journeys a year, the additional running costs are UAH 59,7 thousand and the one-off costs UAH 40 thousand. The sensitivity analysis showed that implementation of the method pays back in less than four months even if the modelled losses are overstated twentyfold.

The sensitivity analysis of the design parameters showed that the pretension non-uniformity coefficient and the required stability margin have a noticeable effect on the result, while the permissible reduction in capacity and the friction corrections have a weak effect. The need for lashings is affected most strongly by their lashing capacity: moving from 2 500 daN to 5 000 daN webs reduces the total number of lashings by 37 %.

The priority task for experimental research is therefore to refine the pretension non-uniformity coefficient.

The results of this chapter were obtained in model calculations and need field verification. At the same time, they justify treating improved securing as a measure for increasing the integrity reliability of the supply chain, and this is how the measure is considered in Chapter 8.

CHAPTER 6.

THE CROSS-BORDER ROAD CORRIDOR AS AN ENVIRONMENT IN WHICH INTEGRITY FAILURES ARISE

Chapters 3–5 dealt with a single load unit on a single vehicle. We now move to the level of the supply chain. The composite indicator of integrity reliability to be constructed in Chapter 7 requires a specific environment in which the real failure factors can be identified and their distribution across the stages of the carriage process and the external disruptions can be assessed. The environment chosen is the cross-border road corridors on the EU's eastern border, and the link between Ukraine and Poland is taken as an example. Since 2022, it has become one of the busiest overland supply routes between Ukraine and the EU market.

Such corridors are of interest for reliability theory for three reasons. Carriage in them is governed by European and international rules, but the part of the route outside the EU runs under conditions that differ substantially from the Union's internal market. The chain thus combines two risk environments.

At the border, the cargo passes between two customs and legal regimes, and the duration of this transition is the least predictable component of delivery time. Finally, a large share of the flow consists of agri-food products whose qualitative integrity depends especially on time and temperature.

6.1. Legal conditions of carriage in the corridor

In traffic between EU states and neighbouring countries, road transport is the most flexible link, carrying products with a high value per unit of mass. Bulk and liquid cargo travel largely by rail and sea. For Ukraine, this role is especially significant.

According to figures published by Deputy Minister for Development of Communities and Territories S. Derkach, in 2025 road transport accounted for 40 % of Ukraine's exports by value and 73 % of imports, while its share of exports by weight was only 9 % [40]. It is therefore by road that the most valuable part of the freight flow moves, and the loss from a single integrity failure per consignment is highest here.

The contractual basis of carriage in the corridor is formed by the CMR Convention and its Additional Protocol on the electronic consignment note (see Section 1.3). The electronic consignment note creates a legal basis for automated recording of the condition of the cargo and of reservations at the moment of handover. This is directly linked to the concept of an integrity failure tied to the act of handover (Section 2.4).

Access of third-country carriers to the EU transport market is determined by agreements, and their time-limited nature itself becomes a source of uncertainty. The Agreement between the EU and Ukraine on the carriage of freight by road, concluded on 29 June 2022, abolished the permit requirement for bilateral and transit operations [1].

The Agreement has been extended several times. In September 2025, it was extended for another 15 months, until March 2027, while retaining the requirements for licensing, vehicle marking and cargo documentation [47]. From the point of view of reliability theory, the legal regime of the corridor is a parameter with a limited period of validity that requires a new political decision each time. Regulatory uncertainty is one of the external factors of chain stability and must be taken into account in the resilience component of the composite indicator.

Customs procedures are simplified by the Convention on a Common Transit Procedure, which operates on the basis of the New Computerised Transit System (NCTS) [10]. Electronic exchange of customs information reduces the number of repeated clearance operations at the crossing point and the time the cargo spends in the customs control zone. Ukraine became a party to the Convention on 1 October 2022 [67].

6.2. Border crossing points and crossing procedures

Crossing the EU external border is the stage at which the cargo stays stationary longest and is least controlled by the cargo owner. Freight traffic on the Polish–Ukrainian section of the border is concentrated at a small number of crossing points that differ in capacity and specialisation (Table 6.1).

Electronic queue management systems have become an important tool for organising traffic. They allow drivers to wait for their turn at a location of their choice rather than at the border. On exit from Ukraine, this function is performed by the eCherha system, which has introduced separate queues for empty trucks at the largest crossing points. One rule is revealing for the integrity issue: trucks carrying goods that require special storage conditions and that collect the cargo shortly before crossing the border register in the queue for loaded vehicles, and the system keeps their place [70]. In effect, this is a recognition that waiting time at the border is a factor of qualitative loss of integrity for perishable goods, and that queue management can serve as a risk reduction tool. At the same time, the electronic queue does not eliminate waiting but only moves it from the border

zone to another place. For cargo that has already been loaded, the duration of standing with the refrigeration unit running remains an important parameter.

Table 6.**1 Main crossing points for road freight on the Polish–Ukrainian section of the border**

Crossing point (Polish / Ukrainian side)	Voivodeship	Characteristics for freight traffic
Dorohusk / Yahodyn	Lubelskie	The largest freight route on this section; according to the State Border Guard Service of Ukraine, the normal capacity of the Yahodyn point is 1 200–1 400 trucks a day in both directions [45]
Hrebenne / Rava-Ruska	Lubelskie	One of the three largest freight routes
Korczowa / Krakovets	Podkarpackie	One of the three largest freight routes; access to the A4 motorway
Medyka / Shehyni	Podkarpackie	Significant freight flow
Zosin / Ustyluh	Lubelskie	Freight and passenger traffic
Dołhobyczów / Uhryniv	Lubelskie	Freight and passenger traffic

Source: compiled by the authors

The border stage has several specific features. Here the cargo may be subjected to physical inspection, scanning or sampling for phytosanitary or veterinary control. Each opening of the cargo space is a potential point at which the seal, the securing or the temperature regime may be breached. After an inspection, the cargo is often re-secured, and nobody checks the quality of this re-securing.

The duration of the stage is the most variable: under normal conditions it is measured in hours, but during disruptions, as shown in Section 6.4, it can reach several days. It is therefore advisable to single out the border stage in the chain model and to treat its duration as a random variable that affects the probability of failure at this and subsequent stages.

6.3. Stage structure of the carriage process and failure factors

According to the definition proposed in Section 2.4, an integrity failure is recorded at the moment the cargo is handed over from one chain participant to another. For a cross-border corridor, this requires breaking the carriage process down into stages whose boundaries coincide with changes in the responsible participant or in the conditions under which the cargo is kept.

On the basis of the systematisation of sources of integrity risk carried out in the authors' earlier study [63] and the specific features of the corridor, seven stages were identified (Fig. 6.1, Table 6.2).

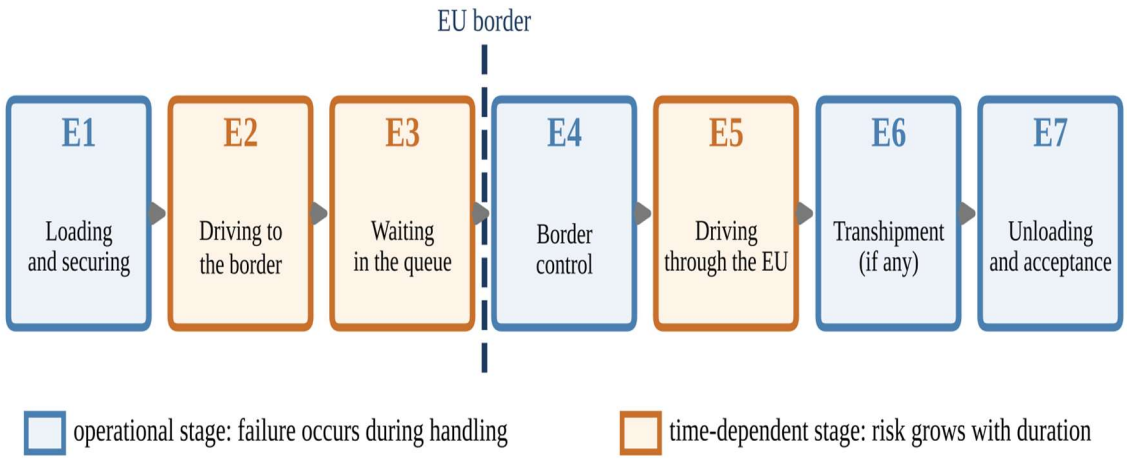


Fig. 6.1**. Stages of the carriage process in the cross-border corridor**
Source: developed by the authors

Table 6.2 **Stages of the carriage process in the cross-border corridor and their characteristic integrity failures**

Stage	Content	Responsible participant	Main factors of loss of integrity	Predominant failure types (Table 2.4)	Data sources
E1	Preparatio, loading and securing of the cargo	Consignor, carrier	Inadequate packaging, picking errors, incorrect stowage and securing, insufficient pre-cooling	Partial quantitative, qualitative hidden	Loading reports, entries in the consignment note, temperature at loading
E2	Driving through the country of dispatch to the border	Carrier	Road condition, driving pattern, loosening of securing, refrigeration unit operation, theft at parking areas	Qualitative apparent, pre-failure state	Telematics, temperature loggers, driver reports
E3	Waiting in the queue and at buffer areas	Carrier	Waiting time, unguarded parking, interruptions in power to the refrigeration unit	Pre-failure state, qualitative hidden, total (theft)	Electronic queue data, telematics, loggers
E4	Border and customs control	Carrier, control authorities, customs broker	Inspection and opening of the cargo space, sampling, seal replacement, re-securing	Pre-failure state, partial quantitative	Inspection reports, seal numbers, NCTS records
E5	Driving through EU countries	Carrier	Theft at unguarded parking areas, roadside securing inspections, driving and rest times	Total, partial quantitative, qualitative apparent	Telematics, inspection reports, incident notifications

Table continued 6.2

E 6	Transhipment or cross-docking (if any)	Logistics operator	Mechanical damage during handling, incomplete sets, breaks in the cold chain	Qualitative apparent, partial quantitative	Warehouse reports, WMS records
E 7	Unloading and acceptance by the consignee	Carrier, consignee	Improper unloading, incomplete acceptance by quality, document discrepancies	All types, including detection of hidden failures from earlier stages	Acceptance reports, reservations under CMR Art. 30, claims

Source: developed by the authors

The decomposition allows several observations.

The stages differ in the nature of failures. At stages E1, E6 and E7, which involve handling operations, mechanical damage and quantitative discrepancies predominate; they arise instantly and are mostly apparent. At stages E2, E3 and E5, where the cargo is moving or parked, failures that accumulate over time predominate: deterioration of perishable goods, loosening of securing, theft. As D. Ekwall and B. Lantz showed, different locations in the transport chain have different seasonal patterns of theft [15, 16]. Their data also show that a large proportion of incidents are associated with vehicle parking locations. The probability of failure at the “time-dependent” stages therefore depends on how long the cargo stays there, while at the “operational” stages it is determined by how well specific operations are performed.

The place of detection does not coincide with the place of origin. Many failures that arise at stages E1–E6 are recorded only at stage E7. A hidden failure caused, for example, by a prolonged temperature excursion at the border may be established only after the carriage has been completed. Standard accounting then attributes the event to the final stage and distorts the picture of how reliability is distributed along the chain. This gap can be closed only by systematically accumulating monitoring data at each stage, which makes it possible to establish at which stage the condition of the cargo began to deviate from the norm. For this reason, pre-failure states recorded by telematics and temperature loggers are used in the assessment as independent information.

The stages are interdependent. The quality of pre-cooling at stage E1 determines how much time the cargo can safely wait at stage E3. The quality of securing at stage E1 determines how sensitive the cargo is to the driving pattern at stages E2 and E5. This link follows directly from the results of Chapters 3–5. Securing with an insufficient stability margin turns every critical section of road into a source of risk, and loss of pretension during driving gradually increases the probability of failure at later stages of the route. European guidelines require stowage and securing to keep the cargo stable under all normal driving conditions, including emergency braking and manoeuvring [18]. The stages therefore cannot be considered independent, as in the simplified model (2.1), and the composite indicator must take the link between them into account.

The stages have different responsible parties and different data sources. Calculating reliability components for each stage is possible only if the chain participants exchange information rather than merely record the outcome of their own stage. The electronic consignment note and digital systems at the border create not only organisational but also methodological prerequisites for this.

6.4. External disruptions in 2022–2026

The factors considered in Section 6.3 act within individual stages and are largely controlled by the chain participants. External disruptions, by contrast, arise outside the chain. The participants cannot eliminate them and can neutralise them only partly, through sound management and technological decisions [63]. In 2022–2026, the corridors on the EU's eastern border were characterised by four groups of such disruptions.

Socio-political disruptions are linked to protests that affect the operation of crossing points. In 2023–2024, truck traffic through a number of crossing points on the Polish–Ukrainian border was restricted for long periods during protests by carriers and farmers. According to the State Border Guard Service of Ukraine, almost 3,5 thousand trucks were queuing at the border in early December 2023 [23].

Such episodes matter for reliability theory because the duration of the border stage can suddenly increase by an order of magnitude or more, and its distribution has a heavy tail. A restriction on one route redistributes the flow to other crossing points and lengthens the queues there, so the disruption spreads through the network. For perishable goods, waiting for several days inevitably

turns a pre-failure state into a qualitative failure. It is such episodes that account for most of the losses, which are not reflected in average indicators.

Regulatory disruptions. After the EU's temporary restrictions on imports of certain grains and oilseeds expired on 15 September 2023, Poland, Hungary and Slovakia introduced national restrictions on imports of Ukrainian agricultural products [71]. Such decisions do not affect integrity directly. They do, however, change the structure of the flow, force rerouting and increase the share of transport carried out under uncertainty about whether the cargo will be admitted. The time-limited nature of the road transport agreement, whose extension depends each time on a new decision of the parties, is of a similar character.

Security disruptions in the country of dispatch. Military action damages warehouse and transport infrastructure, causes forced stoppages, lengthens routes to the border and creates a shortage of qualified drivers. For the carriage process, this means a risk of total failure for cargo held in a warehouse or terminal and an indirect effect on the quality of work through work intensification and the involvement of less experienced staff. The latter also applies to securing: inexperienced staff make the errors systematised in Table 3.4 more often.

Criminal threats. After crossing the border, the cargo enters an environment in which the main threat to quantitative integrity is organised theft. According to TAPA EMEA, in February 2026 alone 1 168 cargo thefts were recorded in Europe, the Middle East and Africa, and the total value of losses in cases with an estimate reached almost EUR 166,5 million [37].

The reported data cover only incidents notified by association members and law enforcement agencies, so the real scale of the phenomenon is larger. For the carrier, the risk of total failure at stage E5 depends on the choice of parking places and security arrangements, not only on the route.

The mechanism by which disruptions affect integrity is summarised in Table 6.3.

Table 6.3 **External disruptions in the cross-border corridor and the mechanism of their effect on integrity failures**

Disruption group	Examples (2022–2026)	Stages affected	Mechanism of effect	Failures whose probability increases
Socio-political	Protests at crossing points (2023–2024)	E3, E4	Multiple increase in waiting time, redistribution of the flow	Qualitative hidden, pre-failure state; total for perishable goods
Regulatory	National restrictions on agri-food imports, time-limited agreements	E1, E4, E7	Changes in routes and transport regime, uncertainty about admission	Indirectly all types, through a longer chain
Security	Damage to warehouses and terminals, forced stoppages, driver shortage	E1, E2, E6	Destruction of cargo, traffic stoppages, lower quality of work	Total, qualitative apparent, pre-failure state
Criminal	Theft of cargo and vehicles	E3, E5	Deliberate removal of cargo, mainly at unguarded parking areas	Total, partial quantitative

Source: developed by the authors

External disruptions act on the chain through two channels: by increasing the time the cargo spends at the time-dependent stages and by directly removing or destroying the cargo. The first channel is decisive for qualitative integrity, the second for quantitative integrity. This leads to a methodological conclusion for Chapter 7.

The resilience component of the composite indicator must reflect the sensitivity of the failure probability to waiting time. The probability of total failure events, in turn, must be taken into account in the probability component through the intensity of the corresponding threats at each stage.

6.5. Quantitative risk structure across the stages of the model route

Sections 6.3 and 6.4 described the failure factors qualitatively. Before constructing the indicator, it is useful to estimate, at least approximately, what share of the total failure probability each risk source contributes. Such an estimate serves two purposes. It shows at which stages the risk is concentrated and thus suggests where measures should be directed. It also makes it possible to check whether the model parameters used in Chapter 8 are consistent with the qualitative picture of the corridor.

The estimate uses the journey model described in detail in Section 8.1: a route from Zhytomyr Oblast to Wrocław via the Krakovets – Korczowa crossing point, two types of products (chilled berries and sunflower oil on pallets), two chain organisation variants (without monitoring, and with monitoring and guarded parking) and two border waiting scenarios (typical S1 and blockade S3).

The failure probability from each source was calculated by formulas (7.1)–(7.3) with the parameters of Table 8.2. Since the probabilities are small, the share of a source in the total failure probability can be estimated as the ratio of its probability to the sum of the probabilities of all sources.

The results are given in Table 6.4.

Table 6.4 **Shares of risk sources in the total probability of integrity failure on the model route, %**

Risk source	Perishable, A, S1	Perishable, A, S3	Perishable, B, S1	Non-perishable, A, S1	Non-perishable, A, S3	Non-perishable, B, S1
Operational failures at E1 (loading)	10,9	3,7	12,4	26,7	20,2	37,3
Operational failures at E4 (inspection)	8,2	2,8	9,3	13,4	10,1	18,7
Operational failures at E7 (unloading)	8,2	2,8	9,3	20,1	15,1	28,0
Loosening of securing at E2 and E5	14,4	4,9	4,9	35,2	26,6	14,7
Theft at E2 and E5	0,7	0,3	0,3	1,6	1,2	0,9
Theft while waiting (E3)	1,2	5,0	0,1	3,0	26,9	0,4
Qualitative failures at normal temperature	55,8	67,6	63,5	–	–	–
Qualitative failures due to temperature excursions at E3	0,8	13,1	0,2	–	–	–
Total failure probability per journey, %	3,67	10,75	3,23	1,50	1,98	1,07

Source: calculated by the authors (model estimate)

The risk structure is fundamentally different for the two types of products. For perishable products, more than half of the failure probability comes from the natural loss of quality during transport, and in the blockade scenario this share rises to two thirds. Added to this are failures due to temperature excursions during waiting, whose share in a blockade grows from 0,8 to 13,1 %. For perishable cargo, the main resource for increasing reliability is therefore reducing time on the road, and especially waiting time, together with temperature control. This is consistent with the fact that in Chapter 8 priority queue registration and monitoring have the highest specific effectiveness for this cargo.

For non-perishable products, the picture is different. Under typical conditions, the largest risk source is loosening of securing during the driving stages (35,2 %), and together with operational failures during loading and

unloading (46,8 %) mechanical factors account for more than 80 % of the failure probability. This is why improved securing proved to be the most effective measure for this cargo (Chapter 8). In the blockade scenario, theft during waiting comes to the fore (26,9 %): cargo standing for several days at an unguarded parking area becomes an attractive target.

Monitoring and guarded parking (variant B) change the risk structure as expected. The share of theft during waiting falls almost to zero, and the share of loosening of securing falls by a factor of two to three, because loosening is detected and corrected before the cargo shifts. As a result, the relative share of operational failures at the loading, inspection and unloading stages increases. This does not mean that they have become more frequent. The other risk sources have simply decreased, and operational failures have become the main reserve for further improving reliability.

This leads to a conclusion that is important for the choice of measures: measures that are effective for one cargo may be secondary for another, even on the same route. For perishable cargo, time and temperature are decisive; for packaged general cargo, the quality of handling and securing. The composite indicator constructed in Chapter 7 must reflect this difference, which is achieved by using different component weights for the two types of cargo.

6.6. Seasonal variation of risks and transport planning

Integrity risks in the corridor vary over the year. For cargo theft, seasonality has been established empirically: D. Ekwall and B. Lantz found annual and weekly seasonality of incidents that differs between locations in the transport chain [15, 16]. For the qualitative integrity of perishable goods, the decisive factor is the ambient temperature, on which the load on the refrigeration unit depends. For mechanical integrity, winter conditions are important: a wet or icy deck reduces friction (Section 4.3), and the deterioration of roads in winter and spring accelerates the loosening of securing (Section 3.5).

Let us estimate the effect of winter conditions on the integrity reliability of the non-perishable goods chain using the model of Chapter 8. Winter conditions are represented by two parameter changes: the rate of securing loosening at the driving stages is increased 1,6-fold, and the probability of mechanical damage during loading is increased by 0,0015 because of worse handling conditions. Both changes are scenario assumptions. The results for the typical border waiting scenario are given in Table 6.5.

Table 6.5 **Effect of winter conditions on chain integrity reliability (non-perishable products, scenario S1)**

Chain variant	Season	P_{int}	K_P	K_T	K_D	I_{int}	Level	Expected losses, EUR per journey
A (no measures)	Summer	0,985	0,707	0,588	0,228	0,600	Reduced	43,6
A (no measures)	Winter	0,981	0,619	0,463	0,229	0,549	Reduced	57,8
A + improved securing (M4)	Summer	0,991	0,825	1,000	0,212	0,687	Adequate	26,4
A + improved securing (M4)	Winter	0,989	0,771	0,762	0,224	0,646	Adequate	33,9
B (monitoring and guarded parking)	Summer	0,989	0,788	0,838	0,844	0,848	High	24,3
B (monitoring and guarded parking)	Winter	0,987	0,744	0,675	0,846	0,799	Adequate	30,2
B + improved securing (M4)	Summer	0,993	0,866	1,000	0,848	0,906	High	15,1
B + improved securing (M4)	Winter	0,991	0,828	1,000	0,841	0,890	High	19,5

Source: calculated by the authors (model estimate)

Winter conditions lower the indicator in all chain variants, but to different extents. The regularity component loses most: as failures become more frequent, the median interval between them shortens, and in the base variant K_T falls from 0,588 to 0.463. Variant B, which provides a high level of reliability in summer, drops to adequate in winter (0,799), i.e. monitoring and guarded parking on their own do not compensate for the seasonal increase in mechanical risks. Only in combination with improved securing does the chain retain a high level of reliability in winter (0,890), and its expected losses in winter remain lower than those of variant B in summer.

Two conclusions follow for transport planning. The first concerns seasonal adjustment of measures. Improved securing, which pays for itself for non-perishable goods even in summer (Chapter 8), becomes even more effective in winter, because mechanical factors account for a larger share of failures in this

period. The second concerns reliability assessment. An indicator calculated for the summer period overestimates the annual reliability of the chain, so the minimum observation period of 12 months (Table 7.6) must cover all seasons, and chains should be compared using indicators for the same periods.

Conclusions to Chapter 6

The cross-border road corridor on the EU's eastern border combines two risk environments, different customs and legal regimes and a large share of time-sensitive agri-food cargo. Factors of both quantitative and qualitative loss of integrity therefore act in it simultaneously. The legal regime of the corridor contains parameters with a limited period of validity whose extension requires new political decisions each time, and this regulatory uncertainty is one of the external factors of supply chain stability.

The carriage process has been broken down into seven stages whose boundaries coincide with changes in the responsible participant or in the conditions under which the cargo is kept. The stages are divided into "operational" stages, where failures arise during handling, and "time-dependent" stages, where the failure probability grows with the time spent there. The stages are interdependent, in particular through the quality of pre-cooling and of cargo securing at the loading stage. External disruptions in 2022–2026 have been systematised into four groups: socio-political, regulatory, security-related and criminal. They affect integrity by lengthening the time-dependent stages and through the direct removal or destruction of cargo.

A model estimate of the risk structure on the route revealed a fundamental difference between cargo types. For perishable products, more than half of the failure probability comes from the natural loss of quality during transport, and in the blockade scenario temperature excursions during waiting add a noticeable share. For packaged general cargo under typical conditions, more than 80 % of the failure probability is due to mechanical factors, mostly loosening of securing while driving, and in the blockade scenario theft at parking areas comes to the fore. Measures that are effective for one cargo may therefore be secondary for another, even on the same route.

A model estimate of seasonal changes showed that winter conditions reduce the integrity reliability of the packaged general cargo chain in all organisational variants, and only the combination of monitoring with improved securing retains a high level of reliability in winter.

CHAPTER 7.

A COMPOSITE INDICATOR OF INTEGRITY-ORIENTED SUPPLY CHAIN RELIABILITY

7.1. Principles of indicator design

Constructing a composite indicator involves resolving a sequence of methodological questions: choosing a theoretical framework, selecting partial indicators, normalising, weighting and aggregating them, and checking the robustness of the result. This sequence is described in detail in the OECD and European Commission Joint Research Centre handbook on constructing composite indicators [55], on which the proposed approach is based. The theoretical framework is the reliability theory of technical systems [58], and the object of assessment is the integrity reliability of the supply chain in the sense defined in Section 2.2.

The construction of the indicator follows five principles.

The principle of analogy. Each partial component has a counterpart among the classical reliability characteristics: the probability of failure-free operation, mean time to failure, failure severity, maintainability and resistance to external influences. This places the indicator within an established conceptual framework and keeps it interpretable for reliability specialists.

The principle of stage decomposition. Components of a probabilistic nature are first calculated for each stage of the carriage process (E1–E7, Table 6.2) and then aggregated to the chain level. This makes it possible not only to assess reliability but also to find the stages that reduce it most.

The principle of non-compensability. A high value of one component must not fully compensate for a critically low value of another. A chain in which failures are rare but each of them means total loss of the cargo cannot be considered reliable merely because failures are rare. This principle determines the choice of a multiplicative aggregation model (Section 7.4).

The principle of separating predictive and actual information. The indicator combines components calculated from the chain model (predictive) and components determined from actual failure data (empirical). This allows the indicator to be used both for assessing an existing chain and for comparing design alternatives for which no actual data yet exist.

The principle of reproducibility. All input data must be obtained from documents and systems already used in the corridor: CMR and e-CMR consignment notes, acceptance reports, telematics data, temperature loggers, electronic queue records and NCTS.

7.2. Indicator structure and partial components

On the basis of these principles, a composite indicator of integrity-oriented supply chain reliability I_{int} is proposed, consisting of five normalised components (Table 7.1, Fig. 7.1).

Table 7.1 **Structure of the composite indicator of integrity-oriented reliability**

Sym	Component	What it measures	Counterpart in reliability theory	Nature of information
K_P	Probability	Probability of delivery without an integrity failure over all stages	Probability of failure-free operation	Predictive (stage model)
K_T	Regularity	Conformity of the actual interval between failures with the consignee's requirements	Mean time to failure	Empirical
K_S	Severity	Share of cargo value retained in the event of a failure	Severity of failure consequences	Empirical
K_D	Detection and response	Ability to detect pre-failure states and prevent them from turning into failures	Maintainability, testability	Empirical
K_R	Resilience	Sensitivity of the probability of failure-free delivery to disruptions in the duration of time-dependent stages	Resistance to external influences	Predictive (stage model)

Source: developed by the authors

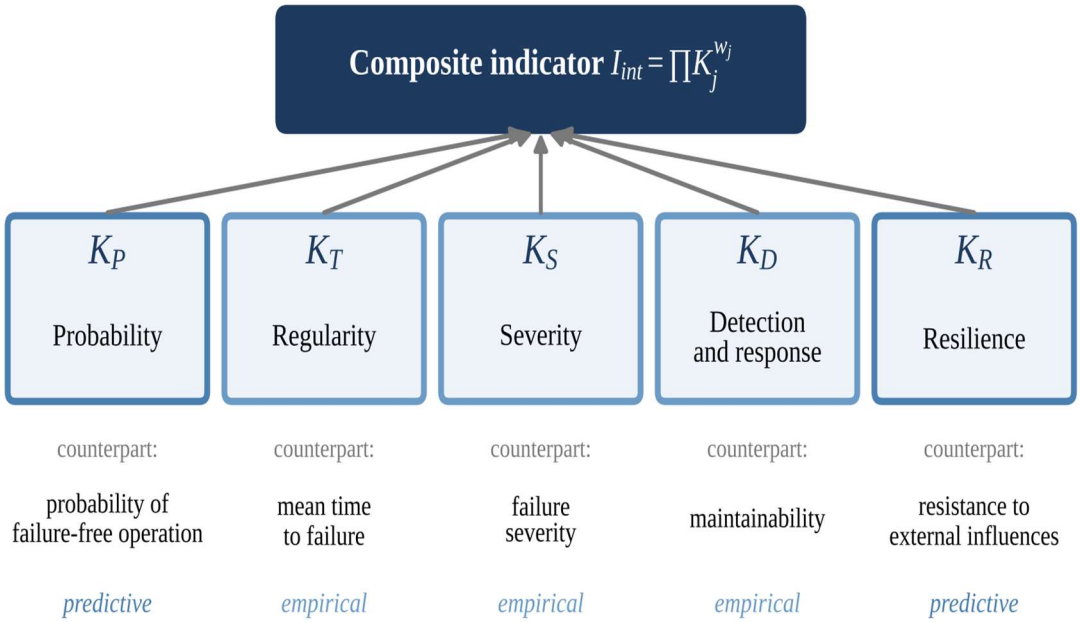


Fig. 7.1. **Structure of the composite indicator of integrity-oriented supply chain reliability**

Source: developed by the authors

All components are 111haracteri to the interval [0; 1], where 1 corresponds to the best state. Each component reflects a separate requirement from Table 2.3, and none duplicates another. The regularity component K_T does not repeat the probability component K_P: the latter 111haracterizes the predicted probability of failure per consignment, while K_T reflects the actual time structure of failures, including their clustering typical of periods of disruption. The resilience component K_R does not include total failure events caused by extreme events, since these are taken into account in the probability component. It reflects only how far the probability of failure-free delivery falls when moving from typical to unfavourable conditions.

7.2.1. Failure probability at a stage

The starting quantity for both predictive components is the probability q_i that an integrity failure of any type occurs at the i-th stage ($i = 1, \dots, 7$). Several independent risk sources act at each stage [63]. Following fault tree logic [78], the

probability q_i is therefore determined as the probability that at least one of the elementary events connected by an OR gate occurs:

$$q_i = 1 - \prod_{k=1}^{K_i}(1 - q_{ik}), \tag{7.1}$$

where q_{ik} is the probability of failure at the i-th stage from the k-th risk source;

K_i is the number of risk sources at the i-th stage.

For the operational stages (E1, E4, E6, E7), the probabilities q_{ik} are estimated statistically as the share of consignments with a failure from the corresponding source, or by expert judgement when statistics are lacking. For the time-dependent stages (E2, E3, E5), the failure probability increases with the time the cargo spends there. Assuming a constant failure rate, as is standard for the exponential reliability model [58],

$$q_i(t_i) = 1 - e^{-\lambda_i t_i^{eq}}, \tag{7.2}$$

where λ_i is the rate of integrity failures at the i-th stage, h^{-1};

t_i^{eq} is the equivalent duration of the cargo's stay at the stage, h.

An equivalent rather than actual duration is needed because, for perishable goods, the rate of quality loss depends on temperature. In food technology, this dependence is described by the temperature coefficient Q_{10}, which shows by what factor the rate of spoilage changes when the temperature changes by 10 °C [39]. The equivalent duration of a stage equals the sum of the intervals during which the cargo was kept at different temperatures, reduced to the recommended transport temperature:

$$t_i^{eq} = \sum_{j=1}^{J_i} \Delta t_{ij} \cdot Q_{10}^{(\theta_{ij} - \theta_{ref})/10}, \tag{7.3}$$

where Δt_{ij} is the duration of the j-th interval at the i-th stage, h;

θ_{ij} is the cargo temperature during this interval, °C;

θ_{ref} is the recommended transport temperature, °C;

J_i is the number of intervals identified from the temperature logger data.

For example, a cargo with a recommended temperature of 2 °C and an assumed value of $Q_{10} = 2{,}5$ spent 3 h at 10 °C while waiting at the border because of a power failure of the refrigeration unit. The equivalent duration of this interval is $3 \cdot 2{,}5^{0{,}8} \approx 6{,}2$ h. In terms of quality loss, a three-hour excursion is equivalent

to more than six hours of transport under normal conditions. For non-perishable goods, no temperature correction is applied ($Q_{10} = 1$), and the main risk sources at the time-dependent stages are theft and loosening of securing.

Loosening of securing has the same time-dependent nature. Lashing tension decreases under vibration and cyclic loading in proportion to the distance travelled (Chapter 3). The rate of pre-failure states of the "loosened securing" type at the driving stages therefore depends on the quality of the initial securing. It is through this parameter that the stage model takes into account the effect of the improved method of Chapter 4.

7.2.2. Probability component

The probability of delivery without an integrity failure at all stages is calculated as

$$P_{int} = \prod_{i=1}^{7}(1 - q_i) \tag{7.4}$$

Unlike the simplified model (2.1), here the probabilities at the time-dependent stages depend on duration and temperature. The stages are thus linked through common factors: the quality of pre-cooling at E1 determines the cargo temperature at later stages, the quality of securing at E1 determines the rate of its loosening at E2 and E5, and the waiting time at E3 affects the total equivalent transport duration. This way of accounting for interdependence does not require complex models of dependent failures and at the same time reflects the main mechanisms linking the stages identified in Section 6.3.

For real chains, P_{int} is usually close to one, and practically significant differences between chains are concentrated in a narrow range of its values. If P_{int} were used directly, this component would hardly affect the composite indicator, even though it is the main reliability characteristic. We therefore apply linear 113ormalization relative to a minimum acceptable level, which is recommended for composite indicators when substantively justified scale limits are known [55]:

$$K_P = \max\left(0;\ \frac{P_{int} - P_{int}^{min}}{1 - P_{int}^{min}}\right), \tag{7.5}$$

where P_{int}^{min} is the minimum acceptable probability of delivery without failure, below which the chain is considered unacceptable regardless of its other characteristics.

The value of P_{int}^{min} is set according to the type of cargo and the consignee's requirements. For example, with $P_{int}^{min} = 0{,}88$, a chain with $P_{int} = 0{,}94$ obtains $K_P = 0{,}50$, and a chain with $P_{int} = 0{,}99$ obtains $K_P = 0{,}92$. A difference of five percentage points in probability, which would look insignificant if P_{int} were used directly, becomes a substantial difference in the normalised component. Normalisation thus reflects the practical significance of this difference for the cargo owner.

7.2.3. Regularity component

The regularity component characterises the actual time structure of failures. Consignments are ordered in time, and for each pair of successive failures the number of consignments between them is determined. The component is calculated as

$$K_T = \min\left(1;\ \frac{\tilde{T}_m}{T_{req}}\right), \tag{7.6}$$

where $\tilde{T}_m$ is the median number of consignments between successive failures over the observation period;

T_{req} is the required (contractual) number of consignments between failures, set according to the consignee's requirements or the carrier's target quality level.

Using the median rather than the mean is essential here. If failures are evenly distributed in time, the two characteristics are close. If failures cluster, as happens during periods of disruption, the mean remains large thanks to long failure-free periods, while the median falls substantially, reflecting the series of failures. In this way K_T responds to systemic problems of the chain that cannot be seen from the average failure frequency.

7.2.4. Severity component

The severity component reflects the share of cargo value that is retained in the event of a failure:

$$K_S = 1 - \frac{1}{m}\sum_{j=1}^{m}\frac{\Delta V_j}{V_j}, \tag{7.7}$$

where m is the number of failures over the observation period;

ΔV_j is the value of the lost part of the cargo, or the amount by which its value decreased, in the j-th failure;

V_j is the value of the cargo in the consignment in which the j-th failure occurred.

The meaning of ΔV_j is consistent with the way compensation is determined under Articles 23 and 25 of the CMR. In the case of loss or shortage, it equals the value of the lost cargo; in the case of damage, the amount by which the value decreased. The input data for calculating K_S can therefore be taken directly from claim files and acceptance reports. A total failure corresponds to $\Delta V_j / V_j = 1$. If such failures predominate, the component approaches zero.

7.2.5. Detection and response component

This component characterises the chain's ability to detect a pre-failure state during carriage and to prevent it from turning into a failure. It equals the product of two coefficients:

$$K_D = d \cdot r = \frac{n_{det}}{n_{pf}} \cdot \left(1 - \frac{n_{tr}}{n_{det}}\right), \tag{7.8}$$

where n_{pf} is the total number of pre-failure states over the period, including those established retrospectively after a failure;

n_{det} is the number of pre-failure states detected during carriage by monitoring equipment or by staff;

n_{tr} is the number of detected pre-failure states that turned into failures despite intervention;

d is the detection coefficient; r is the response effectiveness coefficient.

This component formalises a property that none of the common indicators reflects (Table 2.3) and is a direct counterpart of maintainability in reliability theory.

Pre-failure states also include cases of loosened securing found during en-route checks. A schedule of securing checks on CLS sections (Chapter 4) therefore directly increases the coefficient d. A chain without monitoring equipment and without a check schedule has d close to zero, even if failures in it are rare. Its

reliability rests on favourable conditions and will disappear as soon as conditions worsen.

7.2.6. Resilience component

The resilience component characterises the sensitivity of the probability of failure-free delivery to disruptions in the duration of the time-dependent stages, above all waiting at the border. Waiting time is a non-negative random variable with right skewness. It is conveniently described by the log-normal distribution, which is common for quantities formed as the product of many independent factors [43]. For this distribution, the 50th and 95th percentiles are related by

$$t_{95} = t_{50} \cdot e^{1{,}645\sigma}, \tag{7.9}$$

where t_{50} is the median waiting time, h;

t_{95} is the duration not exceeded in 95 % of cases, h;

σ is the dispersion parameter of the logarithm of the duration.

The resilience component equals the ratio of the probabilities of failure-free delivery under unfavourable and typical waiting times:

$$K_R = \frac{P_{int}(t_{95})}{P_{int}(t_{50})}. \tag{7.10}$$

If only the failure probability at stage E3 depends on waiting time and the temperature regime during waiting is normal, the formula simplifies to $K_R = \exp[-\lambda_3(t_{95} - t_{50})]$. Let the conditional failure rate be $\lambda_3 = 0{,}0015$ h^{-1} and the median waiting time 5 h. With moderate dispersion ($\sigma = 0{,}8$), we obtain $t_{95} \approx 18{,}6$ h and $K_R \approx 0{,}980$. With the dispersion typical of blockade periods ($\sigma = 1{,}3$), we obtain $t_{95} \approx 42{,}4$ h and $K_R \approx 0{,}945$ respectively. With an unchanged median, greater variability of waiting reduces the resilience component (Fig. 7.2).

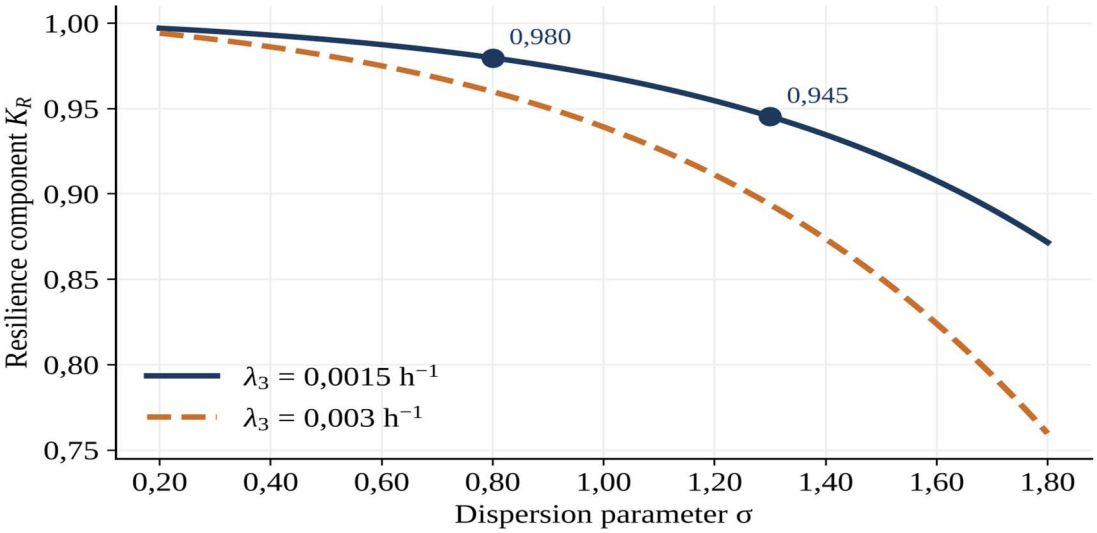


Fig. 7.2. **Resilience component as a function of the dispersion parameter of waiting time (t_{50} = 5 h)**

Source: developed by the authors

This is exactly what is required: the component must distinguish between chains that perform equally under typical conditions but behave differently during disruptions.

The calculation formulas and input data sources for all components are summarised in Table 7.2.

Table 7.2 **Input data for calculating the partial components**

Component	Main input quantities	Data sources
K_P	q_{ik} for operational stages; λ_i, Δt_{ij}, θ_{ij}, Q_{10} for time-dependent stages; P_{int}^{min}	Acceptance reports, claims statistics, temperature loggers, telematics, electronic queue data
K_T	Sequence of consignments with failures marked; T_{req}	Register of consignments and claims, contracts with consignees
K_S	$\Delta V_j, V_j$	Claim files, discrepancy reports, accompanying documents
K_D	n_{pf}, n_{det}, n_{tr}	Monitoring logs, en-route securing inspection reports, incident reports
K_R	t_{50}, σ (or t_{95}); failure rates at time-dependent stages	Electronic queue and telematics data, failure statistics at stage E3

Source: developed by the authors

7.3. Determination of weighting coefficients

The contributions of the components to the composite indicator are not equal, and their relative importance depends on the type of cargo, the consignee's requirements and the corridor conditions. In practice, there is usually no statistical basis for determining the weights, such as sufficiently long observation series, so the weights are best determined from expert judgements. The most common tool for this is T. Saaty's analytic hierarchy process, based on pairwise comparison of criteria and a check of the consistency of judgements [62]. An expert judgement of how many times one component is more important than another is, however, always approximate, and expressing it as a single number creates an illusion of precision. A fuzzy modification of the method (fuzzy AHP) was therefore used, in which judgements are expressed by triangular fuzzy numbers in accordance with L. Zadeh's fuzzy set theory [82].

Among the methods for calculating weights in fuzzy AHP, the most common are D.-Y. Chang's extent analysis method [7] and J. Buckley's geometric mean method [5]. Chang's method is popular because of its simplicity, but, as Y.-M. Wang, Y. Luo and Z. Hua showed, it can assign zero weights to criteria that actually have non-zero importance [81]. The geometric mean method was therefore applied. The procedure for determining the weights consists of six steps. Each expert fills in a pairwise comparison matrix of the five components with linguistic judgements corresponding to triangular fuzzy numbers (l, m, u): "equal importance" (1, 1, 1); "weak preference" (1, 2, 3); "moderate preference" (2, 3, 4); "between moderate and strong" (3, 4, 5); "strong preference" (4, 5, 6). Reciprocal judgements correspond to the reciprocal numbers $(1/u, 1/m, 1/l)$.

The consistency of each matrix is checked using the matrix of mean values m: the maximum eigenvalue λ_{max}, the consistency index $CI = (\lambda_{max} - n)/(n-1)$ and the consistency ratio $CR = CI/RI$ are calculated, where for $n = 5$ the random index is $RI = 1{,}12$ [62]. A matrix with $CR > 0{,}10$ is returned to the expert for revision.

The individual matrices are aggregated into a group matrix by element-wise geometric averaging of the fuzzy numbers.

For each component, the fuzzy geometric mean of the row of the group matrix is calculated:

$$\tilde{r}_i = \left(\left(\prod_{j=1}^{n} l_{ij}\right)^{1/n};\ \left(\prod_{j=1}^{n} m_{ij}\right)^{1/n};\ \left(\prod_{j=1}^{n} u_{ij}\right)^{1/n} \right). \qquad (7.11)$$

The fuzzy weights are determined as $\tilde{w}_i = (r_{li}/\sum r_u;\ r_{mi}/\sum r_m;\ r_{ui}/\sum r_l)$, where the sums are taken over all components.

The fuzzy weights are converted into crisp ones by the centroid method $w_i^* = (w_{li} + w_{mi} + w_{ui})/3$ and normalised: $w_i = w_i^*/\sum w_i^*$.

The procedure is illustrated by a matrix reflecting the typical position of an owner of perishable agri-food cargo. The probability component has a moderate preference over the regularity component and a weak preference over the others. The severity and resilience components have a weak preference over regularity. The remaining pairs are judged equally important.

The matrix of mean values is given in Table 7.3.

Table 7.3 **Matrix of mean values of pairwise comparisons (perishable cargo)**

Component	K_P	K_T	K_S	K_D	K_R
K_P	1	3	2	2	2
K_T	1/3	1	1/2	1	1/2
K_S	1/2	2	1	1	1
K_D	1/2	1	1	1	1
K_R	1/2	2	1	1	1

Source: developed by the authors

For this matrix, $\lambda_{max} = 5{,}052$, $CI = 0{,}013$, $CR = 0{,}012$, i.e. the consistency of judgements is high. The results of the weight calculation are given in Table 7.4.

Table 7.4 Weighting coefficients of the components (perishable cargo)

Component	Fuzzy geometric mean $\tilde{r}_i$	Fuzzy weight $\tilde{w}_i$	Normalised crisp weight w_i
K_P	(1,149; 1,888; 2,551)	(0,166; 0,352; 0,631)	0,349
K_S	(0,803; 1,000; 1,246)	(0,116; 0,186; 0,308)	0,185
K_R	(0,803; 1,000; 1,246)	(0,116; 0,186; 0,308)	0,185
K_D	(0,803; 0,871; 1,000)	(0,116; 0,162; 0,247)	0,160
K_T	(0,488; 0,608; 0,871)	(0,071; 0,113; 0,215)	0,121

Source: calculated by the authors

The width of the fuzzy weights reflects the uncertainty of the expert judgements and is used in the sensitivity analysis. If changing the weights within the fuzzy intervals does not change the reliability level of the chain, the assessment result is considered robust to inaccuracy of judgements.

7.4. Aggregation model and interpretation scale

In the practice of composite indicators, additive (weighted sum) and multiplicative (weighted geometric mean) aggregation models are used most often. The additive model implies full compensation: a low value of one component can be offset by a high value of another. Geometric aggregation is less compensatory and better suits cases where the components characterise different, mutually irreplaceable properties of the object [55]. In accordance with the principle of non-compensability, the composite indicator is defined as the weighted geometric mean of the components:

$$I_{int} = K_P^{w_P} \cdot K_T^{w_T} \cdot K_S^{w_S} \cdot K_D^{w_D} \cdot K_R^{w_R}, \quad \sum w = 1. \tag{7.12}$$

The model has three properties that are important for reliability assessment:

if any component equals zero, the indicator also equals zero. A chain whose probability of failure-free delivery is below the minimum acceptable level ($K_P = 0$) is deemed unacceptable regardless of its other characteristics;

the elasticity of the indicator with respect to each component equals its weight: a 1 % change in a component changes the indicator by w_j %, so the weights can be interpreted directly;

the logarithm of the indicator is a weighted sum of the logarithms of the components, which makes it possible to decompose the deviation of the indicator from one into the contributions of individual components.

The difference between the models is illustrated by a hypothetical example with the weights of Table 7.4. Chain A has the values $K_P = 0{,}90$; $K_T = 0{,}80$; $K_S = 0{,}95$; $K_D = 0{,}60$; $K_R = 0{,}95$: its monitoring is not the best, but failures are mostly minor. Chain B has the same K_P and K_R and better $K_T = 0{,}90$ and $K_D = 0{,}70$, but its failures are mostly total, and $K_S = 0{,}20$. Under the additive model, the indicators of the chains are 0,859 and 0,748; under the multiplicative model, 0,849 and 0.661. The multiplicative model increases the difference between the chains

from 0,11 to 0,19 and better reflects the fact that the high regularity and detection in chain B do not compensate for the total loss of cargo in every failure.

Management decisions require not only the value of the indicator but also the reasons for its deviation from one. By the third property of the multiplicative model, the share of the j-th component in the total "reliability deficit" is

$$\delta_j = \frac{w_j \ln K_j}{\ln I_{int}}, \quad \sum_j \delta_j = 1. \tag{7.13}$$

Similarly, the share of the i-th stage in the total failure probability can be estimated as $\varepsilon_i = \ln(1 - q_i)/\ln P_{int}$. Both decompositions indicate in which component and at which stage the reserves for improving reliability are concentrated, and they are used in Chapter 8 to select measures.

Indicator values are interpreted using E. Harrington's desirability scale [27], which is widely used in multi-criteria assessment to convert dimensionless indicators into linguistic ratings. The interval limits of the scale (0,20; 0,37; 0,63; 0,80) correspond to characteristic points of the desirability function. Applying them to an indicator constructed as the geometric mean of components is substantively consistent, since Harrington proposed overall desirability precisely as the geometric mean of partial desirabilities. The correspondence between intervals and reliability levels is given in Table 7.5.

Table 7.5 **Scale of integrity-oriented supply chain reliability levels**

Value of I_{int}	Level	Interpretation
0,80–1,00	High	The chain ensures integrity with high probability; failures are rare and minor; violations are detected and contained
0,63–0,80	Adequate	The chain meets the requirements, but individual components need improvement
0,37–0,63	Reduced	Reliability is ensured only partly; targeted measures are needed at the stages contributing most to the deficit
0,20–0,37	Low	The chain does not meet the consignee's requirements; the transport technology or organisation must be changed
0,00–0,20	Critical	The chain is unacceptable for this type of cargo

Source: developed by the authors on the basis of the desirability scale [27]

On this scale, chain A from the example has a high level of reliability, and chain B an adequate level, but with only a small margin above the boundary of the reduced level. The diagnostic decomposition for chain B shows that 72 % of its reliability deficit falls on the severity component. Priority measures should therefore be aimed at preventing total failures rather than at further improving regularity. For chain A, by contrast, almost half of the deficit (49,6 %) falls on the detection and response component.

7.5. Assessment algorithm

The proposed models are combined in an eight-step algorithm. Chain description. The route, type of cargo, participants and the boundaries of stages E1–E7 are defined by the points at which the responsible participant or the conditions under which the cargo is kept change. The type of each stage (operational or time-dependent) is established.

Required parameters. On the basis of contracts and the consignee's requirements, P_{int}^{min}, T_{req}, θ_{ref} and, for perishable cargo, Q_{10} are determined.

Data collection and verification. A register of consignments over the observation period is compiled, recording failures and their types (Table 2.4), the value of losses, pre-failure states, stage durations and temperature profiles. Failures detected at acceptance are attributed, on the basis of monitoring data, to the stage at which they arose.

Stage probabilities. For the operational stages, q_{ik} and q_i are determined; for the time-dependent stages, the rates λ_i, the equivalent durations t_i^{eq} and the probabilities $q_i(t_i)$.

Partial components. P_{int} and K_P are calculated, together with the components K_T, K_S, K_D and, on the basis of the waiting time distribution, K_R.

Weights. An expert survey is conducted, the consistency of the matrices is checked and the weights are determined by the fuzzy AHP geometric mean method.

Aggregation and interpretation. I_{int} is calculated, the level is determined from Table 7.5, and the deficit is decomposed by components and stages.

Sensitivity analysis. The robustness of the reliability level to changes in the weights within the fuzzy intervals and to changes in the required parameters is checked.

The reliability of the result depends on the volume and quality of the input data. The minimum requirements for them are set out in Table 7.6.

Table 7.6 **Minimum requirements for input data**

Requirement	Minimum value or condition	Justification
Length of the observation period	At least 12 months	Covers seasonal fluctuations in theft risk, temperature load and road condition [15]
Number of consignments in the register	At least 200	Statistical estimation of failure probabilities at the level of hundredths
Number of failures for calculating K_T	At least 5	Determination of the median interval; with fewer failures, $K_T = 1$ if the number of failure-free consignments is at least T_{req}
Period for recording hidden failures	At least 7 days after delivery	Consistency with the reservation period under CMR Art. 30
Temperature data for perishable cargo	Continuous recording at intervals of no more than 15 min	Identification of excursion intervals for calculating the equivalent duration
En-route securing checks	Result of every check recorded	Accounting for pre-failure states of the “loosened securing” type
Number of experts for determining weights	At least 5	Reduces the influence of individual judgements on the group matrix

Source: developed by the authors

If actual data are insufficient, for example when a new chain is being designed, the algorithm is applied in predictive mode. Stage failure probabilities are determined by expert judgement or by analogy, the components K_T, K_S, K_D are taken at the level typical of the carrier’s similar chains, and the main information for comparing alternatives is carried by the predictive components K_P and K_R. A variant of the predictive mode is simulation, in which all five components are calculated on a generated sequence of journeys. This mode was used for the testing in Chapter 8.

7.6. Properties of the indicator and comparison of aggregation methods

Any composite indicator must satisfy a number of formal requirements, without which its values cannot be trusted. Guidelines on constructing composite indicators stress that the choice of aggregation method is not a technical detail: it determines how the indicator behaves in borderline cases and whether this behaviour is consistent with the purpose of the assessment [55]. Let us check what properties the proposed indicator has and compare it with two alternatives.

Formal properties. Indicator (7.12) has five properties that follow directly from its construction.

Boundedness. All components lie in the interval [0; 1], the weights are positive and sum to one, so $0 \leq I_{int} \leq 1$. The value 1 is reached only when all components equal one.

Monotonicity. Increasing any component while the others remain unchanged cannot reduce the indicator. Any measure that improves at least one property of the chain without worsening the others therefore raises the score.

Non-compensability. If any component equals zero, the indicator also equals zero, regardless of the values of the other components. This is not the case for the additive model.

Interpretability of weights. The elasticity of the indicator with respect to the j-th component equals its weight w_j. The weight thus shows directly by how many per cent the indicator changes when the component changes by 1 %.

Decomposability. The logarithm of the indicator equals the weighted sum of the logarithms of the components, so the reliability deficit decomposes into the contributions of the components without remainder (formula (7.13)).

Comparison of aggregation methods. Alongside the weighted geometric mean, let us consider two other methods: the weighted sum (additive model) and the minimum of the components (the “weakest link” model). The results of the calculation for all twelve test cases of Chapter 8 are given in Table 7.7.

Table 7.7 **Indicator values under different aggregation methods (levels: H – high, A – adequate, R – reduced, L – low, C – critical)**

Cargo, variant, scenario	Weighted sum	Level	Weighted geometric mean	Level	Minimum of components	Level
Perishable, A, S1	0,714	A	0,655	A	0,241	L
Perishable, A, S2	0,610	R	0,565	R	0,236	L
Perishable, A, S3	0,320	L	0,262	L	0,131	C
Perishable, B, S1	0,827	H	0,818	H	0,686	A
Perishable, B, S2	0,754	A	0,743	A	0,638	A
Perishable, B, S3	0,525	R	0,479	R	0,286	L
Non-perishable, A, S1	0,659	A	0,600	R	0,228	L
Non-perishable, A, S2	0,644	A	0,585	R	0,222	L
Non-perishable, A, S3	0,577	R	0,516	R	0,194	C
Non-perishable, B, S1	0,850	H	0,848	H	0,788	A
Non-perishable, B, S2	0,847	H	0,844	H	0,787	A
Non-perishable, B, S3	0,832	H	0,829	H	0,779	A

Source: calculated by the authors

The comparison yields three observations.

First, the ranking of chains by the weighted sum and by the geometric mean is the same in this example (Spearman's rank correlation coefficient equals 1,0). The choice between these two methods therefore does not change the answer to the question of which chain is more reliable. It changes the absolute values and hence the assignment to levels of the scale.

Second, the weighted sum systematically gives higher values, and the difference is greatest where one of the components is low. For non-perishable products in the base variant (detection component about 0,22), the additive model places the chain at the adequate level and the geometric model at the reduced level. The additive model thus allows a chain that is almost unable to detect violations to obtain an "adequate" rating thanks to high values of the other components. For reliability management purposes, such compensation is undesirable.

Third, the “weakest link” model is too strict. It completely ignores all components except the worst one. All six cases of the base variant A fall into the low or critical level, although these chains differ substantially in the probability of failure-free delivery. Moreover, this model does not allow the reliability deficit to be decomposed into the contributions of the components and therefore gives no indication of which measures to choose. Its rank correlation with the geometric mean is 0,874, i.e. the ranking of the chains changes.

The weighted geometric mean occupies an intermediate position: it does not allow full compensation but takes all components into account. This confirms the choice made in Section 7.4.

Effect of the minimum acceptable probability. Another parameter that affects the value of the indicator is P_{int}^{min} in formula (7.5). Lowering this threshold raises the normalised probability component for all chains, but not equally: for chains with a high P_{int} the effect is weaker, and for chains with P_{int} close to the threshold it is stronger. P_{int}^{min} therefore determines how severely the indicator “penalises” chains with a low probability of failure-free delivery. Its value should be set by the cargo owner according to the value of the cargo and the consequences of failure. For the assessments of different chains of the same cargo owner to be comparable, P_{int}^{min} must be the same for all chains being compared.

7.7. The indicator in regular monitoring mode

In actual mode, the indicator is calculated from the consignment register for a certain period. If the chain is assessed regularly, for example monthly, the question arises of which period the data should cover. A short period makes the indicator sensitive to change but unstable: a few random failures can change its value substantially. A long period smooths random fluctuations, but the indicator responds to change with a delay. Let us consider this trade-off using a model example.

We simulate 24 months of operation of the perishable products chain in the variant with monitoring and guarded parking (variant B of Chapter 8), with 150 journeys a month. During the first nine months, the corridor operates in the typical mode (S1). In the tenth month, the load increases (S2); in the eleventh and twelfth a blockade occurs (S3); in the thirteenth and fourteenth the load remains elevated; and from the fifteenth month the corridor returns to the typical mode. The indicator is calculated monthly over a six-month moving window. The components K_P, K_T, K_S and K_D are determined from the simulated events in the window, and

the component K_R as the mean value for the scenarios of the months in the window. The results are shown in Fig. 7.3.

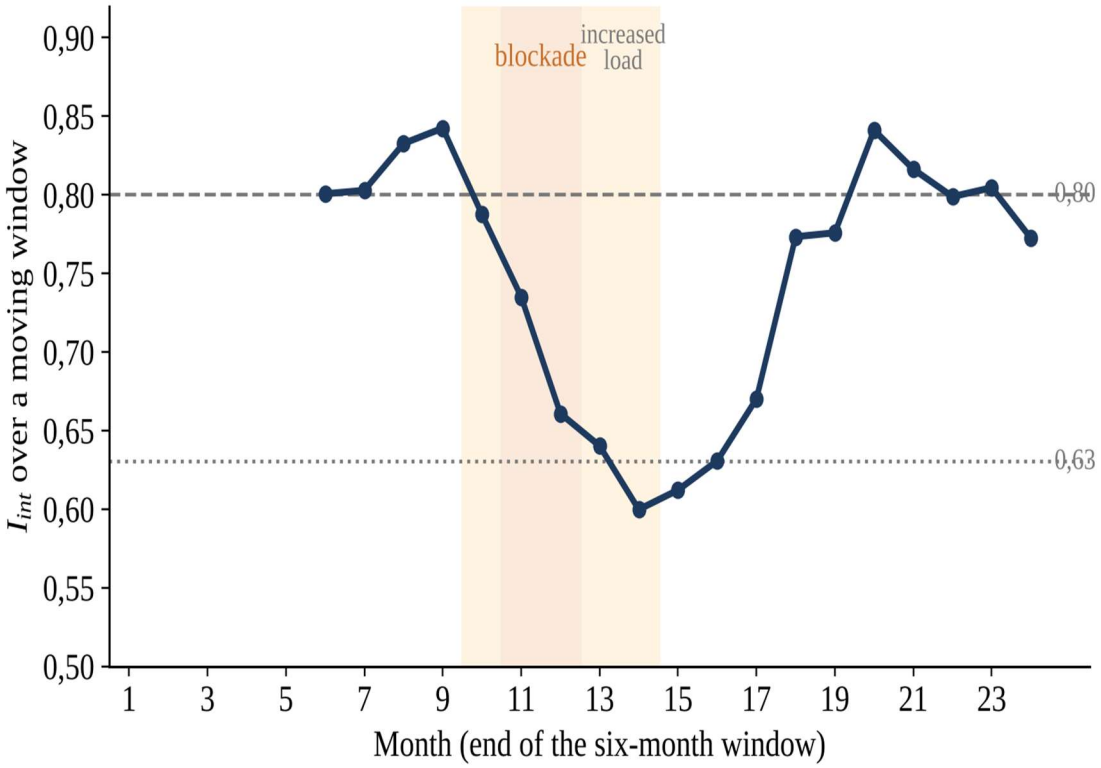


Fig. 7.3. **Values of the composite indicator over a six-month moving window (model example)**
Source: developed by the authors

During the period of typical operation, the indicator fluctuates between 0,80 and 0.84. These fluctuations are random: there are 22–24 failures in the 900 journeys of a window, and each failure affects the median interval and the mean severity to a greater or lesser extent. With the onset of the period of increased load, the indicator falls and reaches a minimum of 0,599 in the window ending in the fourteenth month, i.e. two months after the blockade ended. It returns to a level above 0,80 in the twentieth month, when the window is completely free of months with disruptions.

The six-month window therefore responds to disruptions with a noticeable delay: the lowest value of the indicator is recorded after the disruption has passed, and recovery takes another six months. For assessing reliability as a characteristic of the chain, this is acceptable and even desirable, since the indicator should reflect

stable properties rather than the current state. For operational management, the delay is too long. In monitoring mode it is therefore advisable to use two windows: a long one (6–12 months) for assessing chain reliability and comparing it with other chains, and a short one (1–2 months) for early detection of deterioration. The short window contains few failures, and the components K_T and K_S calculated over it are unstable. The component K_D and the share of journeys with pre-failure states, however, are calculated from a much larger number of events and can serve as early indicators.

7.8. Use of the indicator in contractual relations

The composite indicator can be not only a tool of internal analysis but also the basis of a cargo owner's contractual requirements for a carrier. At present, such requirements are formulated mainly in terms of delivery time, the share of perfect orders and a cap on claims. As shown in Chapters 2 and 8, these characteristics do not reflect the chain's ability to preserve the cargo under different conditions. Let us consider how the indicator can be used at three stages of contractual relations: when choosing a carrier, while the contract is being performed and when it is reviewed.

Choosing a carrier. In a tender, the cargo owner can require bidders to provide data sufficient to calculate the indicator in predictive mode: a description of how transport is organised (whether there is monitoring, a response procedure, guarded parking, a securing method), failure statistics for the previous year and the results of an internal audit. Comparing bidders by the indicator calculated with the same required parameters and weights reflects their ability to preserve the cargo more accurately than comparing them by price and the declared share of perfect orders. The results of Chapter 8 show that two carriers with almost the same share of perfect orders can differ in the indicator by 0,16–0,31, i.e. by one or two levels of the scale.

Performing the contract. It is advisable to include three groups of terms in the contract. The first group sets the required parameters: the minimum acceptable probability of delivery without failure, the required interval between failures, the target level of the indicator and the minimum acceptable level under unfavourable conditions. The second group sets the obligations regarding data: which events the carrier records, in what form and within what time limits it passes them to the cargo owner. The third group sets the consequences: what happens if the actual value of the indicator falls below the target. Such

consequences may include a joint analysis of causes using the diagnostic decomposition, a corrective action plan and, in the event of systematic non-performance, a review of the contract terms.

Reviewing the contract. The diagnostic decomposition of the reliability deficit (formula (7.13)) gives the parties a common language for discussing changes. If the deficit is concentrated in the severity component, the subject of negotiation is measures against total losses. If it is in the resilience component, the discussion concerns the organisation of border crossing. If it is in the probability component for the loading stage, responsibility lies partly with the consignor, and measures must be agreed with it. Such a division makes it possible to avoid mutual recriminations and to direct efforts to the stages where they are most effective.

Using the indicator in contracts also has limitations. The indicator is calculated from data that are partly generated by the carrier itself, so the cargo owner should be able to verify these data, for example through access to telematics and logger records. In addition, the value of the indicator over a short period is unstable (Section 7.7), so contractual requirements should be formulated for a period of no less than six months. Finally, the required parameters must be the same for all carriers that the cargo owner compares; otherwise the comparison is meaningless.

Conclusions to Chapter 7

The composite indicator of integrity-oriented reliability has been constructed on the principles of analogy with reliability theory, stage decomposition, non-compensability, separation of predictive and actual information, and reproducibility. It consists of five components: probability, regularity, severity, detection and response, and resilience.

The failure probability at the time-dependent stages is determined by an exponential model with an equivalent duration that, for perishable cargo, takes the temperature profile into account through the coefficient Q_{10}. The quality of cargo securing is taken into account through the rate of pre-failure states of the "loosened securing" type at the driving stages and through their detection coefficient. The probability component is normalised relative to a minimum acceptable level, which increases its discriminating power.

The regularity component uses the median interval between failures and is therefore sensitive to their clustering, while the resilience component is defined as the ratio of the probabilities of failure-free delivery at the 95th percentile and

the median of waiting time.The weights are determined by the fuzzy analytic hierarchy process with geometric mean calculation, and for perishable cargo the probability component has the largest weight (0,349). Aggregation by the weighted geometric mean ensures non-compensability and allows the reliability deficit to be decomposed by components and stages, and the values of the indicator are interpreted on Harrington's five-level desirability scale.

The indicator satisfies the requirements of boundedness, monotonicity, non-compensability, interpretability of weights and decomposability. Comparison with alternative aggregation methods showed that the weighted sum ranks chains in the same way but allows a chain with a very low ability to detect violations to obtain an adequate rating, while the "weakest link" model is too strict and does not allow the reliability deficit to be decomposed. The weighted geometric mean occupies a justified intermediate position between them. A model example of regular monitoring showed that a six-month moving window responds to disruptions with a delay of about two months and recovers over six months, so for operational management it should be supplemented by a short window and early indicators.

A procedure has been proposed for using the indicator in contractual relations between cargo owner and carrier: when choosing a carrier, for formulating contractual requirements on required parameters, data exchange and the consequences of non-performance, and when reviewing the contract on the basis of the diagnostic decomposition of the reliability deficit.

CHAPTER 8.

TESTING THE COMPOSITE INDICATOR AND SELECTING RELIABILITY IMPROVEMENT MEASURES

8.1. Purpose, object and conditions of testing

The purpose of the testing is not to assess the reliability of a particular company but to check three properties of the proposed indicator. First, whether it distinguishes between chains that traditional indicators regard as identical. Second, whether it responds to external disruptions in line with the corridor analysis in Chapter 6. Third, whether it provides a sound basis for choosing reliability improvement measures, in particular for assessing improved cargo securing alongside other measures. The testing was carried out in predictive mode (Section 7.5) by statistical simulation. The chain parameters were set on the basis of open data on the corridor and scenario assumptions of the authors. The resulting figures illustrate the properties of the method and do not describe real carriers.

The object of testing is a supply chain for agricultural products delivered by road from a production site in Zhytomyr Oblast to a distribution centre in Wrocław via the Krakovets – Korczowa crossing point (Table 6.1). The driving time to the border (stage E2) is taken as 8 h, and through Poland (stage E5) as 6 h. The carriage is performed as a direct journey, so there is no transhipment stage E6.

Two types of products that differ in sensitivity to time and temperature are considered: perishable (chilled berries, recommended temperature 2 °C) and non-perishable (sunflower oil in bottles, packed on pallets), for which the temperature factor is not taken into account. For each type, two chain organisation variants are considered. Variant A (base) does not provide continuous remote monitoring. Breaches of the temperature regime, loosened securing or attempts to access the cargo space are detected mainly by the driver, and waiting at the border takes place at unguarded parking areas. Variant B provides online transmission of logger and telematics data, a procedure for prompt response to deviations, and waiting at guarded parking areas. External disruptions are represented by three scenarios of border waiting time with a log-normal distribution (Table 8.1). Scenario S1 corresponds to normal operation with an electronic queue, S2 to periods of increased load, and S3 to a blockade similar to the events of late 2023.

Table 8.1 **Scenarios of border waiting time (scenario assumptions)**

Scenario	Median duration t_{50}, h	Dispersion parameter σ	Duration t_{95}, h
S1 – typical operation	5	0,8	18,6
S2 – increased load	14	0,9	61,5
S3 – blockade	36	1,3	305,5

Source: developed by the authors

The journey model covers four groups of events.

Failures at operational stages. At stages E1, E4 and E7, a failure occurs with a constant probability. Failure severity (share of value lost) is uniformly distributed between 2 and 15 %.

Theft attempts. They occur at a rate that depends on the stage and the type of parking and are pre-failure states. A detected attempt is prevented with probability 0,3 in variant A and 0,7 in variant B. A successful theft means total loss with probability 0,3, and partial loss (10–40 % of value) in the remaining cases.

Loosening of securing. At the driving stages E2 and E5, it occurs at a rate of $1{,}2 \cdot 10^{-3}$ h^{-1} and is also a pre-failure state. Undetected loosening turns into mechanical damage to the cargo with probability 0,40, and detected and corrected loosening with probability 0.06. The severity of such damage is 5–30 % of value.

Temperature excursions (perishable products only). During waiting at the border, they occur at a rate of 0,012 h^{-1} and raise the cargo temperature by 8 °C. A detected excursion is corrected within 0,5 h, while an undetected one lasts until the end of waiting. The probability of a qualitative failure is calculated by formulas (7.2)–(7.3) from the equivalent duration of the whole journey. The severity of a qualitative failure increases with the duration of the excursion from 30 % to total loss.

The detection coefficient of pre-failure states is 0,25 in variant A and 0,90 in variant B. The other model parameters are given in Table 8.2. The failure probabilities and rates were chosen so that the total share of consignments with a failure is between one and several per cent.

Table 8.2 **Input parameters of the simulation**

Parameter	Perishable products	Non-perishable products	Status of the value
Failure probabilities at stages E1, E4, E7	0,004; 0,003; 0,003	0,004; 0,002; 0,003	Assumption
Duration of stages E1 / E2 / E4 / E5 / E7, h	2 / 8 / 1,5 / 6 / 1,5	2 / 8 / 1,5 / 6 / 1,5	Estimate based on route length
Rate of theft attempts at E2 / E5, h^{-1}	$1{,}0 \cdot 10^{-5}$ / $3{,}0 \cdot 10^{-5}$	$1{,}0 \cdot 10^{-5}$ / $3{,}0 \cdot 10^{-5}$	Assumption
Rate of theft attempts at E3: unguarded / guarded parking, h^{-1}	$7{,}0 \cdot 10^{-5}$ / $1{,}8 \cdot 10^{-5}$	$7{,}0 \cdot 10^{-5}$ / $1{,}8 \cdot 10^{-5}$	Assumption
Rate of qualitative failures at the recommended temperature, h^{-1}	$8{,}0 \cdot 10^{-4}$	not taken into account	Assumption
Temperature coefficient Q_{10}	2,5	1,0	Assumed value [39]
Minimum acceptable probability P_{int}^{min}	0,88	0,95	Required parameter
Required interval between failures T_{req}, consignments	20	80	Required parameter
Required delivery time, h	48	72	Required parameter
Value of cargo per consignment, thousand EUR	38	22	Assumption

Source: developed by the authors

For each of the 12 combinations of cargo type, chain variant and scenario, 400 000 journeys were simulated. The probability component was calculated as the share of journeys without failure, and the components K_T, K_S and K_D from the simulated sequence of failures, their severity and pre-failure states. The component K_R was calculated by formula (7.10) in a separate simulation with fixed

waiting times t_{50} and t_{95}. The calculations were performed in Python with a fixed random number generator seed, which ensures reproducibility.

8.2. Weighting coefficients

The full procedure for determining the weights (Section 7.3) involves surveying at least five independent experts from among cargo owners, carriers and insurers. Since the testing is methodological, the weights were determined from the agreed judgement of the authors, formed in the light of the results of Chapters 2 and 6. This limitation is taken into account in the sensitivity analysis (Section 8.5).

Different pairwise comparison matrices were used for the two types of products. For perishable products, the matrix of Table 7.3 was applied, in which the severity and resilience components take priority over regularity, because it is waiting time and total spoilage that determine the cargo owner's main losses. For non-perishable products, sensitivity to waiting time is insignificant, so the resilience component received the lowest priority. Regularity, which reflects the frequency of claims and the associated administrative costs, was judged as important as severity and detection. The matrix for non-perishable products has $\lambda_{max} = 5{,}010$ and $CR = 0{,}002$. The weights are given in Table 8.3.

Table 8.3 **Weighting coefficients of the components for the two types of products**

Component	Perishable: fuzzy weight	Perishable: crisp weight	Non-perishable: fuzzy weight	Non-perishable: crisp weight
K_P	(0,166; 0,352; 0,631)	0,349	(0,160; 0,349; 0,646)	0,343
K_T	(0,071; 0,113; 0,215)	0,121	(0,112; 0,185; 0,315)	0,182
K_S	(0,116; 0,186; 0,308)	0,185	(0,112; 0,185; 0,315)	0,182
K_D	(0,116; 0,162; 0,247)	0,160	(0,112; 0,185; 0,315)	0,182
K_R	(0,116; 0,186; 0,308)	0,185	(0,055; 0,098; 0,220)	0,111

Source: calculated by the authors

For both types of products, the probability component has the largest weight, which corresponds to its role as the main reliability characteristic. The

differences between the matrices come down to a redistribution of priorities between resilience and regularity. For the same route, the importance of individual chain properties is determined by the cargo.

8.3. Assessment results

The simulation results for perishable products are given in Table 8.4 and for non-perishable products in Table 8.5. The values of the composite indicator for all cases are shown in Fig. 8.1.

Table 8.4 **Components and composite indicator for perishable products**

Variant, scenario	P_{int}	K_P	K_T	K_S	K_D	K_R	I_{int}	Level
A, S1	0,964	0,701	1,000	0,684	0,241	0,988	0,655	Adequate
A, S2	0,951	0,588	0,700	0,573	0,236	0,950	0,565	Reduced
A, S3	0,896	0,131	0,350	0,336	0,218	0,726	0,262	Low
B, S1	0,968	0,736	1,000	0,686	0,871	0,989	0,818	High
B, S2	0,957	0,643	0,800	0,638	0,857	0,961	0,743	Adequate
B, S3	0,914	0,286	0,400	0,554	0,793	0,797	0,479	Reduced

Source: calculated by the authors

Table 8.5 **Components and composite indicator for non-perishable products**

Variant, scenario	P_{int}	K_P	K_T	K_S	K_D	K_R	I_{int}	Level
A, S1	0,985	0,707	0,588	0,865	0,228	0,999	0,600	Reduced
A, S2	0,985	0,690	0,562	0,848	0,222	0,997	0,585	Reduced
A, S3	0,981	0,610	0,450	0,779	0,194	0,983	0,516	Reduced
B, S1	0,989	0,788	0,838	0,895	0,844	1,000	0,848	High
B, S2	0,989	0,787	0,825	0,892	0,842	1,000	0,844	High
B, S3	0,989	0,779	0,787	0,879	0,828	0,998	0,829	High

Source: calculated by the authors

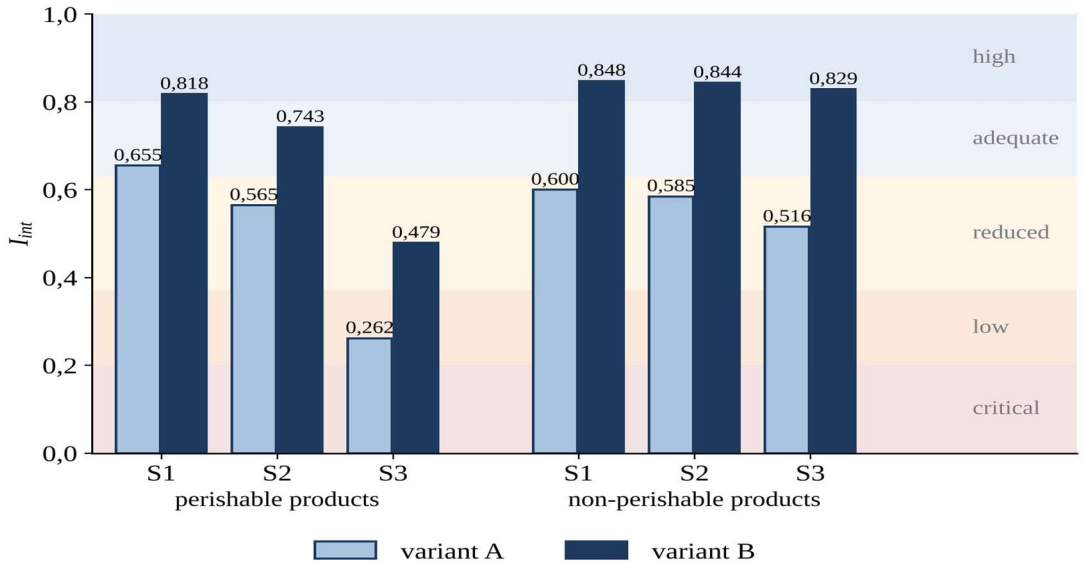


Fig. 8.1. **Composite indicator of integrity-oriented reliability by product type, chain variant and scenario**

Source: developed by the authors

Effect of cargo type. Under typical conditions (S1) in the base variant, the indicator for perishable products is even slightly higher (0,655 versus 0,600), because the low K_T of non-perishable products is associated with a stricter requirement T_{req}. As waiting time increases, the situation changes: in the blockade scenario, the indicator for perishable products falls to 0,262, and for non-perishable products only to 0.516.

The reason is that for perishable products three components deteriorate simultaneously. The probability of failure-free delivery approaches the minimum acceptable level of 0,88, and the normalised component K_P falls to 0.131.

The median interval between failures shortens to 7 consignments. The share of value lost in a failure grows. For non-perishable products, waiting time acts only through the risk of theft, and the changes are much weaker.

Effect of chain organisation. Variant B provides a higher level of reliability in all cases. For non-perishable products, moving from A to B in scenario S1 raises the indicator from 0,600 to 0,848, i.e. from the reduced to the high level.

The probability of failure-free delivery rises only from 0,985 to 0.989. Almost all of the gain in reliability comes from the detection and response component (from 0,228 to 0,844). For perishable products in the blockade scenario, variant B, in addition to detection, substantially improves the severity

component (from 0,336 to 0,554): timely correction of temperature excursions turns some total losses into partial ones.

Effect of external disruptions. Moving from the typical scenario to the blockade reduces the indicator for perishable products in variant A from 0,655 to 0,262 (from the adequate to the low level), and in variant B from 0,818 to 0,479 (from high to reduced).

The resilience component falls from 0,988–0,989 to 0,726–0,797, reflecting the growing sensitivity of the chain to unfavourable conditions.

For non-perishable products, K_R does not fall below 0,983 in any scenario, which is consistent with its meaning: for this cargo, waiting time is not critical.

The shares of the components in the reliability deficit, calculated by formula (7.13), are given in Table 8.6.

Table 8.6 **Shares of the components in the reliability deficit δ_j, %**

Cargo, variant, scenario	K_P	K_T	K_S	K_D	K_R
Perishable, A, S1	29,2	0,0	16,6	53,6	0,5
Perishable, A, S3	52,8	9,5	15,1	18,1	4,4
Perishable, B, S1	53,2	0,0	34,8	11,0	1,0
Perishable, B, S3	59,3	15,1	14,9	5,0	5,7
Non-perishable, A, S1	23,3	18,9	5,2	52,6	0,0
Non-perishable, A, S3	25,6	22,0	6,9	45,2	0,3
Non-perishable, B, S1	49,5	19,6	12,2	18,7	0,0
Non-perishable, B, S3	45,9	23,2	12,5	18,3	0,1

Source: calculated by the authors

In the base variant under typical conditions, the main reserve for improving reliability is the detection and response component, which accounts for 53,6 % of the deficit for perishable and 52,6 % for non-perishable products. Once monitoring is introduced (variant B), the deficit shifts to the probability component and, for perishable products, also to the severity component. Further measures should then be aimed not at detecting violations but at reducing the probability of the failures themselves. This is where improved securing finds its place: it reduces the probability of mechanical damage at stages E1, E2, E5 and E7.

8.4. Comparison with the perfect order indicator

To test the argument of Chapter 2 that common indicators are insufficient, an analogue of the SCOR perfect order fulfilment metric was calculated for each case [29, 53]. It equals the share of journeys in which no integrity failure occurred and the cargo was delivered within the required time (48 h for perishable and 72 h for non-perishable products). The results are given in Table 8.7.

Table 8.7 **Comparison of the composite indicator with the perfect order fulfilment metric**

Cargo, scenario	Perfect order: variant A	Perfect order: variant B	I_{int}: variant A	I_{int}: variant B
Perishable, S1	0,951	0,955	0,655	0,818
Perishable, S2	0,757	0,761	0,565	0,743
Perishable, S3	0,416	0,418	0,262	0,479
Non-perishable, S1	0,984	0,988	0,600	0,848
Non-perishable, S2	0,917	0,921	0,585	0,844
Non-perishable, S3	0,607	0,610	0,516	0,829

Source: calculated by the authors

The comparison confirms two shortcomings of the perfect order fulfilment metric. It does not distinguish between chains with different integrity management. In all scenarios, the values of the metric for variants A and B differ by no more than 0,004, whereas the composite indicator for variant B is higher by 0,16–0.31. Monitoring hardly changes the share of journeys with a failure, but it substantially changes the chain's ability to detect violations and limit their consequences. The perfect order metric records only the final outcome of each journey and does not see this difference.

It mixes timeliness and integrity. For non-perishable products in the blockade scenario, the value of the metric falls to 0,607–0,610, which formally indicates a serious problem in the chain. Yet the probability of delivery without an integrity failure remains at 0,981–0,989, and the composite indicator for variant B stays at the high level (0,829). The decline in the perfect order metric is caused almost entirely by missed delivery deadlines, which for this cargo do not threaten

its integrity. The composite indicator distinguishes between these properties: waiting time affects it only when it increases the risk of an integrity failure.

8.5. Sensitivity to weighting coefficients

To assess how far the conclusions depend on weights determined without a large-scale survey, 5 000 calculations of the indicator were performed for each case with weights drawn at random from triangular distributions corresponding to the fuzzy weights of Table 8.3, followed by normalisation of their sum to one. For each case, the share of calculations in which the reliability level coincides with the base level and the range of values between the 5th and 95th percentiles were determined (Table 8.8).

Table 8.8 **Robustness of the reliability level to variation of the weighting coefficients**

Cargo, variant, scenario	Base I_{int}	Range of I_{int} (5–95 %)	Share with the same level, %
Perishable, A, S1	0,655	0,620–0,689	87,7
Perishable, A, S2	0,565	0,538–0,592	100,0
Perishable, A, S3	0,262	0,234–0,297	100,0
Perishable, B, S1	0,818	0,800–0,839	95,0
Perishable, B, S2	0,743	0,724–0,766	100,0
Perishable, B, S3	0,479	0,443–0,523	100,0
Non-perishable, A, S1	0,600	0,555–0,642	86,6
Non-perishable, A, S2	0,585	0,540–0,625	96,8
Non-perishable, A, S3	0,516	0,475–0,557	100,0
Non-perishable, B, S1	0,848	0,837–0,861	100,0
Non-perishable, B, S2	0,844	0,833–0,857	100,0
Non-perishable, B, S3	0,829	0,818–0,842	100,0

Source: calculated by the authors

In ten of the twelve cases, the reliability level is preserved in at least 95 % of calculations, and in eight cases in all 100 %. Lower robustness (86,6–87,7 %) is observed in two cases where the base value lies near a boundary of the scale (0,655 near the 0,63 boundary and 0,600 near the same boundary). For such cases, the result is best presented as transitional between two levels. The main qualitative conclusions do not change when the weights are varied. The ranges of

values for variants A and B do not overlap in any of the six combinations of cargo and scenario, nor do the ranges for scenarios S1 and S3 within each variant.

8.6. Measures to improve integrity reliability

A reliability assessment has practical value only if it suggests what to change in the chain and whether the costs are justified. The diagnostic decomposition showed in which components the reliability deficit is concentrated, but did not answer which combination of measures to choose with limited resources.

Measures are best classified not by the type of resource (technical, organisational), as is customary in risk management practice, but by which component of the indicator and which stage of the chain they act on. This approach links the choice of measures directly to the results of the diagnostic decomposition. Five measures were selected for the testing, each aimed at one of the main sources of the deficit and implementable by the carrier or the cargo owner without changing the route.

M1. Online monitoring of cargo condition. Temperature loggers and telematics with remote data transmission, together with a procedure for responding to deviations. Modern temperature monitoring technologies contribute substantially to cold chain management [50]. The main effect of the measure is to increase the detection coefficient of pre-failure states and, for perishable cargo, also to shorten temperature excursions and hence reduce the share of total losses.

M2. Guarded parking during waiting. The measure reduces the rate of theft at stage E3. The reference for choosing parking areas is the TAPA PSR standard, which sets requirements for perimeter protection, access control, video surveillance and guarding [14]. According to data published in April 2026, the TAPA EMEA parking network comprised about 230 sites [66], so their availability in a particular corridor is limited.

M3. Pre-cooling and temperature control during loading (perishable cargo only). The measure reduces the probability of failure at stage E1 and the rate of qualitative failures at later stages, because the cargo starts the journey with more time in hand before quality is lost. The importance of temperature control at the point of handover to the carrier is emphasised in review [46].

M4. Cargo securing by the improved method. The measure combines calculating the securing by the algorithm in Table 4.3, using anti-slip mats when

friction is low, a reserve lashing and checks on CLS sections. It reduces the probability of mechanical damage during loading and unloading and the rate of securing loosening at the driving stages. The costs of the measure cover additional lashings, mats, calculation sheets and time for checks.

M5. Priority registration in the electronic queue as cargo requiring special storage conditions (perishable cargo only). The measure uses the electronic queue rule under which a place is kept for trucks that collect such cargo shortly before crossing the border [70]. It shortens the waiting time of perishable cargo and costs almost nothing, but requires the loading schedule to be coordinated with the queue. The parameters adopted for modelling the effect of the measures are given in Table 8.9.

Table 8.9 **Measures to improve integrity reliability and their modelling parameters**

Measure	Stages	Components	Effect in the model (assumption)	Cost, EUR per journey (assumption)	Cargo
M1. Online monitoring	E2–E5	K_D, K_S, K_P	Detection coefficient 0,25 → 0,90; a temperature excursion is corrected within 0,5 h; a detected theft attempt is prevented with probability 0,7	32	Both
M2. Guarded parking	E3	K_P, K_S, K_R	Rate of theft attempts at E3: $7{,}0 \cdot 10^{-5} \rightarrow 1{,}8 \cdot 10^{-5}$ h^{-1}	1,2 per hour of waiting	Both
M3. Pre-cooling	E1–E5	K_P, K_S, K_R	Probability of failure at E1 – 0,001; rate of qualitative failures –20 %	14	Perishable
M4. Securing by the improved method	E1, E2, E5, E7	K_P, K_T, K_S	Probability of failure at E1 – 0,001 (perishable) or –0,002 (non-perishable), at E7 –0,001; rate of securing loosening –60 %	10	Both
M5. Priority queue registration	E3	K_P, K_S, K_R	Waiting time –40 %	4	Perishable

Source: developed by the authors

The values of the effects and costs are scenario assumptions. For practical use, they must be replaced by actual data from the carrier and service providers.

8.7. Model for selecting a combination of measures

The effect of the measures depends on the state of the corridor. A guarded parking area has almost no effect on reliability if waiting lasts a few hours but becomes significant during a blockade lasting several days. Assessing measures under a single scenario is therefore incorrect. Let M denote a combination of measures, $I_s(M)$ and $C_s(M)$ the value of the indicator and the cost per journey in scenario s, and p_s the probability of the scenario. The expected value of the indicator and the expected costs are then

$$\bar{I}(M) = \sum_s p_s\, I_s(M), \quad \bar{C}(M) = \sum_s p_s\, C_s(M). \tag{8.1}$$

To compare individual measures, we introduce specific effectiveness, i.e. the increase in the expected value of the indicator per EUR 100 of expected costs per journey:

$$\eta(M) = \frac{\bar{I}(M) - \bar{I}(\varnothing)}{\bar{C}(M)} \cdot 100, \tag{8.2}$$

where $\bar{I}(\varnothing)$ is the expected value of the indicator for the chain without additional measures.

Specific effectiveness is useful for ranking individual measures but does not solve the problem of choosing a combination, because the effects of measures are not additive. Two measures acting on the same component together give less than the sum of their separate effects. Measures acting on different components may reinforce each other under the multiplicative model. The choice of combination is therefore formulated as the problem of minimising expected costs subject to two constraints:

$$\bar{C}(M) \to \min, \quad \bar{I}(M) \geq I^*, \quad \min_s I_s(M) \geq I_{min}. \tag{8.3}$$

The first constraint requires the expected level of reliability to be no lower than the target I^* set according to the consignee's requirements. The second constraint reflects the resilience requirement: even in the most unfavourable

scenario, the indicator must not fall below the minimum acceptable level I_{min}. With the number of measures typical in practice (up to 8–10), the problem is solved by exhaustive enumeration of all 2^n combinations.

Criterion (8.3) differs from the traditional economic criterion, under which a measure is worthwhile if the reduction in expected losses exceeds its cost. To compare the two approaches, we define the net economic effect per journey:

$$\Delta E(M) = \bar{L}(\varnothing) - \bar{L}(M) - \bar{C}(M), \tag{8.4}$$

where $\bar{L}(M)$ is the expected loss from loss of integrity per journey, i.e. the product of the cargo value and the mean share of value lost.

For the testing, the probabilities of scenarios S1, S2 and S3 are taken as 0,70, 0,25 and 0,05 respectively. The target level $I^* = 0{,}80$ corresponds to the lower boundary of the high level in Table 7.5, and the minimum acceptable $I_{min} = 0{,}63$ to the lower boundary of the adequate level. The simulation was performed for 300 000 journeys for each combination of cargo, scenario and set of measures. The same sequence of random numbers was used for each combination of cargo and scenario, so the differences between combinations are due to the measures themselves rather than to sampling fluctuations. Because of the different sample size, the base values of the indicator may differ from Tables 8.4–8.5 in the third decimal place. The starting point is variant A.

8.8. Results of measure selection

Perishable products. All 32 combinations of the five measures were considered. The highest specific effectiveness belongs to priority queue registration (η = 0,74 per EUR 100), followed by online monitoring (0,54) and pre-cooling (0,20). Securing by the improved method (0,14) and guarded parking (0,04) are less effective for this cargo, because the main losses are associated with quality rather than with mechanical damage or theft. Of the 32 combinations, 11 are Pareto-optimal with respect to expected costs and the expected value of the indicator (Fig. 8.2).

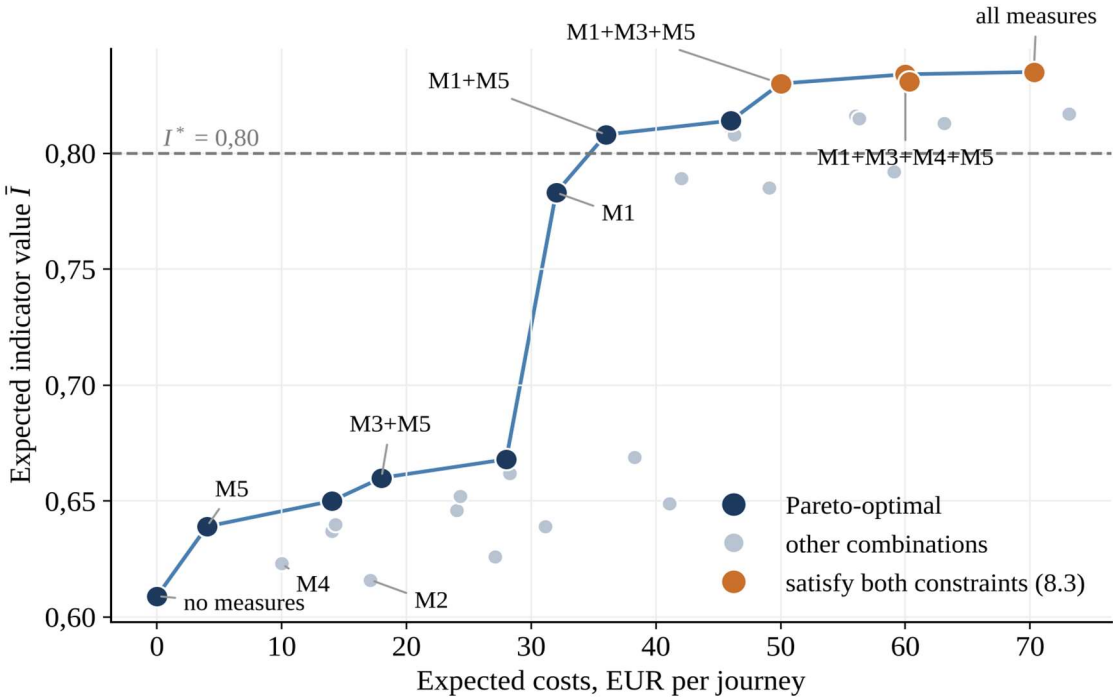


Fig. 8.2. **Combinations of measures for perishable products in the "expected costs – expected indicator value" space**

Source: developed by the authors

The results for individual measures and for the combinations important for the analysis are given in Table 8.10.

Let us compare three selection rules.

Highest return per unit of cost. The combination M3 + M5, at EUR 18 per journey, gives a net effect of +EUR 208,6, the highest return among inexpensive solutions. However, it provides an expected value of only 0,660 (adequate level), and in the blockade scenario the indicator falls to 0.467. A chain that is profitable on average remains vulnerable to disruptions. This vulnerability is hardly visible in mean losses because the blockade scenario has a low probability.

Constraint on the expected level only ($\bar{I} \geq 0{,}80$). The minimum cost is achieved by the combination M1 + M5 (EUR 36, $\bar{I} = 0{,}808$). In the blockade scenario it gives 0,608, i.e. it does not meet the resilience requirement.

Table 8.**10 Simulation results for combinations of measures for perishable products**

Combination	Expected costs, EUR per journey	$\bar{I}$	I, S1	I, S2	I, S3	Expected losses, EUR per journey	ΔE, EUR per journey
No measures	0,0	0,609	0,650	0,565	0,262	635,2	–
M5	4,0	0,639	0,663	0,615	0,414	494,6	+136,6
M4	10,0	0,623	0,662	0,582	0,283	607,2	+18,0
M3	14,0	0,637	0,669	0,603	0,345	528,9	+92,3
M2	17,1	0,616	0,655	0,573	0,278	623,9	–5,8
M3 + M5	18,0	0,660	0,678	0,648	0,467	408,6	+208,6
M1	32,0	0,783	0,819	0,744	0,474	484,9	+118,3
M1 + M5	36,0	0,808	0,828	0,791	0,608	405,9	+193,3
M1 + M4 + M5	46,0	0,814	0,833	0,801	0,615	393,6	+195,6
M1 + M3 + M5	50,0	0,830	0,845	0,819	0,666	329,8	+255,4
M1 + M3 + M4 + M5	60,0	0,834	0,849	0,823	0,678	317,6	+257,7
All five measures	70,3	0,835	0,850	0,824	0,682	314,5	+250,4

Source: calculated by the authors

Both constraints of model (8.3). The optimal combination is M1 + M3 + M5. At EUR 50 per journey, it provides $\bar{I}$ = 0,830 and does not fall below 0,666 in any scenario. Its net economic effect (+EUR 255,4) is only EUR 2,3 less than the maximum, which is given by the combination M1 + M3 + M4 + M5. For perishable cargo, the resilience criterion and the economic criterion therefore almost coincide. The explanation lies in the high value of the cargo and the high expected losses: measures that increase reliability here also reduce losses.

The sequence of Pareto-optimal combinations also shows a rational order for introducing measures with a limited budget: first priority queue registration, then online monitoring, after that pre-cooling and securing.

This order coincides with the results of the diagnostic decomposition (Table 8.6): in the base variant, the main deficit fell on the detection and probability components.

Non-perishable products. Three measures (M1, M2, M4) are applicable to this cargo, i.e. eight combinations (Table 8.11).

Table 8.11 **Simulation results for combinations of measures for non-perishable products**

Combination	Expected costs, EUR per journey	$\bar{I}$	I, S1	I, S2	I, S3	Expected losses, EUR per journey	ΔE, EUR per journey
No measures	0,0	0,592	0,601	0,583	0,513	48,2	–
M4	10,0	0,680	0,695	0,663	0,562	30,0	+8,2
M2	17,1	0,606	0,609	0,603	0,580	40,9	–9,8
M2 + M4	27,1	0,700	0,704	0,697	0,661	22,7	–1,6
M1	32,0	0,843	0,850	0,838	0,785	26,1	–9,9
M1 + M4	42,0	0,897	0,902	0,891	0,854	17,1	–10,9
M1 + M2	49,1	0,853	0,855	0,850	0,835	23,2	–24,1
M1 + M2 + M4	59,1	0,905	0,907	0,904	0,891	14,2	–25,1

Source: calculated by the authors

For non-perishable products, the criteria diverge. Expected losses in the base variant are only EUR 48,2 per journey. The only measure that pays for itself through reduced losses is securing by the improved method (M4): its net effect is +EUR 8,2 per journey, and its specific effectiveness of 0,88 per EUR 100 is the highest among all measures for this cargo. It is thus precisely for non-perishable packaged general cargo, for which mechanical damage is the main type of failure, that improved securing proves to be the most effective first step. This result is consistent with the conclusions of Chapter 5, obtained at the level of an individual journey.

On its own, however, measure M4 gives an expected value of only 0,680, and 0,562 in the blockade scenario. It does not meet the requirements of a high level on average and an adequate level in every scenario. Under both constraints of model (8.3), the optimal combination is M1, with expected costs of EUR 32, $\bar{I}$ = 0,843 and a minimum value of 0.785. If the consignee requires a high level of reliability in every scenario ($I_{min} = 0{,}80$), this is achieved by the combination M1 + M4 for an additional EUR 10 per journey (minimum value 0,854). Under the traditional economic criterion, both combinations are loss-making (–EUR 9,9 and –EUR 10,9 per journey). For this cargo, investment in reliability is justified not by a reduction in direct losses but by the consignee's requirements, and it is the composite indicator that makes it possible to turn these requirements into a

quantitative selection criterion. The divergence of the criteria is not a shortcoming of the indicator. It reflects the fact that the consignee judges the chain not only by the value lost but also by predictability, the frequency of claims and the transparency of the cargo's condition.

8.9. Sensitivity of measure selection to model parameters

The results of Section 8.8 were obtained for specific values of scenario probabilities, costs of measures and required reliability levels.

Table 8.12 **Optimal combinations of measures for different values of the model parameters**

Parameter	Value	Perishable: optimum by (8.3)	Perishable: maximum ΔE	Non-perishable: optimum by (8.3)	Non-perishable: maximum ΔE
Probability of blockade p_{S3}	0,02	M1 + M3 + M5	M1 + M3 + M4 + M5	M1	M4
	0,05 (base)	M1 + M3 + M5	M1 + M3 + M4 + M5	M1	M4
	0,10	M1 + M3 + M5	M1 + M3 + M4 + M5	M1	M4
	0,15	M1 + M3 + M5	M1 + M3 + M4 + M5	M1	M4
Cost of monitoring M1	–40 %	M1 + M3 + M5	M1 + M3 + M4 + M5	M1	M4
	+50 %	M1 + M3 + M5	M1 + M3 + M4 + M5	M1	M4
Minimum acceptable level I_{min}	0,50	M1 + M5	M1 + M3 + M4 + M5	M1	M4
	0,63 (base)	M1 + M3 + M5	M1 + M3 + M4 + M5	M1	M4
	0,70	no solution	M1 + M3 + M4 + M5	M1	M4

Source: calculated by the authors

All of these values are assumptions. Let us therefore check whether the optimal combination of measures changes if these parameters are varied within plausible limits. For each variant, two combinations were determined: the optimum under model (8.3) and the combination with the greatest net economic effect ΔE (Table 8.12).

The structure of the solution proved robust. Changing the probability of a blockade from 0,02 to 0,15, i.e. by a factor of seven and a half, did not change the optimal combinations for either type of product. Only the expected values of the indicator and the economic effect changed. For perishable products, the net effect of the combination M1 + M3 + M4 + M5 rises from EUR 208 to EUR 422 per journey as p_{S3} increases, so the benefit from the measures is greater in periods of elevated blockade risk. Changing the cost of monitoring by –40 % or +50 % also did not change the composition of the optimal combinations. Online monitoring thus remains a necessary element of the solution even if it becomes noticeably more expensive.

Only the required parameter I_{min} proved to be sensitive. If the requirement for the minimum level in the worst scenario is relaxed to 0,50, two measures, M1 + M5, are sufficient for perishable products, which is EUR 14 per journey cheaper. If it is raised to 0,70, none of the 32 combinations satisfies both constraints: even all five measures together give only 0,682 in the blockade scenario. This is an important practical conclusion. For perishable cargo, there is a reliability limit that cannot be reached by measures of the carrier and cargo owner under the existing organisation of the border. A further increase in reliability in the blockade scenario is possible only through measures that shorten the waiting time itself, such as extending priority clearance for perishable goods (Section 9.4).

For non-perishable products, the optimal combination did not change for any of the parameter values considered. The divergence between the economic optimum (M4) and the reliability optimum (M1) also persists in all variants. It is explained by the low direct losses from loss of integrity of such cargo and does not depend on the specific parameter values.

8.10. Limitations of the testing

The test results must be interpreted in the light of several limitations.

Model nature of the data. The failure probabilities and rates and the effects and costs of measures were adopted as scenario assumptions. They were chosen so that the total share of consignments with a failure corresponds to a plausible order of magnitude, but they were not derived from the data of particular carriers. The numerical values of the indicator therefore cannot be used as an assessment of real chains. What is robust are the relative results: the ranking of variants, the direction of the effect of disruptions and the composition of the optimal combinations.

Independence of journeys. In the model, each journey was considered independently of the others. In reality, failures may cluster, for example when one crossing point operates with interruptions for a long time or when one driver systematically secures cargo poorly. Clustering of failures would lower the regularity component, which responds precisely to this, so in real chains the effect of disruptions on the indicator may be stronger than in the model.

Weights without a large-scale survey. The weights were determined by the agreed judgement of the authors. The sensitivity analysis showed that the conclusions are robust to variation of the weights within the fuzzy intervals (Section 8.5), but a full expert survey may shift the priorities, especially for non-perishable cargo.

Simplified model of stage durations. The driving time to the border and through the EU was assumed to be constant. In reality it is also random, especially in the country of dispatch under martial law. Taking this variability into account would increase the sensitivity of the resilience component to disruptions at stages E2 and E5.

One route and two types of cargo. The testing was carried out for one route. For other crossing points, with a different capacity and flow structure, the scenario parameters will be different. The method does not change, but the numerical results need to be recalculated.

These limitations do not invalidate the test results, since the purpose of the testing was to check the properties of the method rather than to assess particular chains. At the same time, they determine which data need to be accumulated to move from the predictive to the actual mode of assessment.

8.11. Effect of incomplete recording of pre-failure states

All the calculations in this chapter assumed that pre-failure states are recorded completely. In practice, this is not the case. A driver who tightened a loosened lashing during a check may not record the fact. A short temperature excursion that passed without consequences may remain only in the logger's memory, from which nobody downloads it. Incomplete recording has the greatest effect on the detection and response component, because it is calculated from the number of pre-failure states.

Let us consider how the assessment changes if only a fraction ρ of the pre-failure states that were detected and corrected is recorded. States that turned into a failure are always recorded, because a failure leads to a claim and a subsequent investigation. The calculation was performed for the non-perishable products chain in variant B in the typical scenario (Table 8.13). The model register of this variant contains 6 884 pre-failure states, of which 6 188 were detected, and 379 of those detected turned into failures.

Table 8.13 **Effect of the completeness of recording of corrected pre-failure states on the reliability assessment (non-perishable products, variant B, scenario S1)**

Share of corrected states recorded ρ	Detection coefficient d	Response coefficient r	K_D	I_{int}	Level
1,00	0,899	0,939	0,844	0,848	High
0,75	0,872	0,920	0,802	0,840	High
0,50	0,825	0,885	0,730	0,826	High
0,25	0,725	0,793	0,575	0,791	Adequate

Source: calculated by the authors

Incomplete recording systematically understates the assessment. If only a quarter of the corrected states are recorded, the detection component falls from 0,844 to 0,575, and the indicator drops from the high to the adequate level. The chain's real ability to detect and correct violations has not changed; only the quality of recording has. The decline occurs through both coefficients: the share of detected states among all recorded states decreases, while the share of detected states that turned into failures increases.

This result has two practical consequences. First, the chains being compared must have comparable recording quality; otherwise, a chain with more thorough recording will gain an advantage without being more reliable. Second, automatic recording of events by monitoring equipment not only increases the real detection capability but also makes the assessment of this capability more accurate. For events recorded by people, such as en-route securing checks, a simple recording form (Appendix B) and the reporting culture described in Section 9.3 are needed. If the completeness of recording is unknown, the detection component should be regarded as a lower bound of the chain's real capability.

Conclusions to Chapter 8

The testing was carried out by statistical simulation on a route from Zhytomyr Oblast to Wrocław via the Krakovets – Korczowa crossing point for two types of products, two chain organisation variants and three scenarios of border waiting time. The journey model takes into account failures at operational stages, theft attempts, loosening of securing and temperature excursions.

The composite indicator distinguishes between chains that the perfect order fulfilment metric regards as identical: with almost the same value of that metric (0,951 and 0,955), the chain carrying chilled berries without monitoring obtained a score of 0,655, and with monitoring 0.818. The perfect order metric mixes timeliness and integrity, so for non-perishable products in the blockade scenario it fell to 0,607, although the probability of delivery without an integrity failure remained at 0.981. The composite indicator responds adequately to external disruptions: for perishable products, moving from the typical scenario to the blockade reduced it from 0,655 to 0,262 without monitoring and from 0,818 to 0,479 with monitoring. The sensitivity analysis with respect to the weights confirmed the robustness of the main conclusions.

The measure selection model showed that for perishable products the combination of online monitoring, pre-cooling and priority queue registration is

optimal under the constraints on the expected and minimum reliability levels. It provides an expected value of 0,830 and no less than 0,666 in the blockade scenario, and its economic effect is only EUR 2,3 per journey less than the maximum. The combination with the highest return per unit of cost left the chain vulnerable in the blockade scenario. For non-perishable products, securing by the improved method is the only measure that pays for itself through reduced direct losses and has the highest specific effectiveness; to achieve a high level of reliability, it should be combined with online monitoring.

The composition of the optimal combinations proved robust to a sevenfold-and-a-half change in the probability of a blockade and to a change in the cost of monitoring from –40 % to +50 %. Only the required reliability level in the worst scenario is sensitive. For perishable products, with a requirement of 0,70, no combination of measures of the carrier and cargo owner achieves it, so a further increase in reliability is possible only by shortening border waiting time. The test results are model-based, and it is mainly the relative conclusions that are robust: the ranking of variants, the direction of the effect of disruptions and the composition of the optimal combinations.

Incomplete recording of corrected pre-failure states systematically understates the reliability assessment: if only a quarter of such states are recorded, a chain with a high level of reliability is rated as adequate, so only chains with comparable recording quality can be compared.

CHAPTER 9.

PRACTICAL IMPLEMENTATION OF THE RESEARCH RESULTS

9.1. Roadmap for implementing EN 12195-1 at a road haulage company

Implementing a standard is often equated with buying the document and issuing an order to apply it. In reality, it means changing everyday operational practices. Such change happens gradually, needs organisational support and inevitably meets resistance from habitual ways of working. Implementation is therefore best planned as a sequence of stages (Table 9.1).

Table 9.1 **Roadmap for implementing EN 12195-1 and the improved method at a road haulage company**

Stage	Content of measures	Responsible	Indicative time frame	Result
1	Diagnosis: documentation, lashing equipment, staff qualifications, procedures, control	Safety department or external consultant	1–2 months	List of gaps ranked by risk
2	Development of a company standard for cargo securing	Technical manager, lawyer	2–3 months	Approved company standard consistent with EN 12195-1
3	Staff training under a differentiated programme	HR department, external trainer	3–4 months	Employees with confirmed competence
4	Calculation sheets for typical loads and routes, identification of CLS sections	Technical department	4–5 months	Set of sheets; less time spent on calculation
5	Provision of lashing equipment, anti-slip mats and measuring instruments	Procurement department	5–6 months	Equipment compliant with EN 12195-2, -3, -4
6	Internal audit of cargo securing	Safety department	from month 6, ongoing	Documented cycle of continuous improvement

Source: developed by the authors

Diagnosis is the step that companies most often skip, although without it neither resources can be planned nor progress measured. It is best carried out in five areas: regulatory documentation, lashing equipment and its condition, staff qualifications, operating procedures and the control system. The result should be a list of shortcomings ranked by risk, which makes it possible to concentrate limited resources where the effect is greatest.

The company standard is the central implementation document. It translates the general requirements of EN 12195-1 into the language of the specific procedures of a particular company. A company standard for securing should include the following elements:

– securing calculation sheets for each typical load, prepared by the algorithm in Table 4.3;

– a procedure for checking the condition of lashing equipment before a journey, including recording of use cycles to calculate the coefficient k_c;

– a schedule of en-route checks: after the first 50–80 km, on CLS sections and every 3–4 hours of driving;

– a securing inspection report form;

– a procedure for reporting deviations and taking corrective action.

Such a document is both a safety management tool and evidence of due diligence in an insurance dispute or administrative proceedings. Records of en-route checks also form a body of data on pre-failure states, which is needed to calculate the component K_D of the composite indicator (Section 7.2.5).

A simplified model for small companies. A small or medium-sized company, which is the typical participant in the Ukrainian road freight market, can start with three steps. The first is to prepare calculation sheets for the five most common loads, which usually cover most journeys.

The second is a one-day practical training course for drivers. The third is to introduce a simple securing checklist that the driver fills in at every loading. These steps require minimal costs and are a genuine first step towards full compliance with the standard.

9.2. Choosing the securing method according to cargo type

A practical tool should be as accurate as possible and as simple as necessary. The choice of securing method is therefore proposed at two levels: a table of typical solutions for standard situations (Table 9.2) and a decision tree for non-standard ones.

Table 9.2 **Recommended securing methods for typical cargo categories**

№	Cargo category	Recommended method	Friction enhancement (mats)	Tipping check
1	Palletised general cargo, crates	Top-over lashing and blocking against the headboard	Mandatory	If the stack is higher than the pallet width
2	Steel coils (eye horizontal)	Direct lashing, wedge chocks, special cradles	Desirable	Yes
3	Sawn timber, long products	Top-over lashing and end stops	Mandatory	No
4	Steel structures of irregular shape	Direct lashing to points on the cargo and blocking	Desirable	Yes
5	Self-propelled machinery and equipment	Wheel chocks and direct lashing to the standard lashing points	Not applicable	Yes
6	Containers	Twist-locks	Not applicable	No
7	Bulk cargo in flexible intermediate bulk containers	Top-over lashing and lateral restraint	Mandatory	Yes
8	Dangerous goods	ADR requirements (Part 7) and EN 12195-1	As calculated	Yes

Source: developed by the authors on the basis of [18, 21, 74]

In all cases, the number of lashings is determined by calculation according to Table 4.3, regardless of any “norms” established at the company.

The logic of the choice is as follows. Top-over lashing is the universal basic solution for most packaged cargo: it increases the pressing force and friction

without requiring lashing points on the cargo itself. With low friction, however, the number of lashings grows rapidly (Table 3.2), and without anti-slip mats this method becomes impractical. Direct lashing is more effective if the cargo has reliable lashing points (eyes, brackets), especially at shallow angles (Section 4.3.2). Blocking is the most reliable method for heavy loads, since it takes the load mechanically and does not depend on lashing tension.

For non-standard situations (unusual shape, uneven mass distribution, mixed consignments, double-deck loading), a decision tree of four questions is proposed.

Is the tipping stability condition $b/(2h_c) > c$ satisfied? If not, a check by (4.3) and securing against tipping are required.

Does the cargo have reliable lashing points? If so, direct lashing is more effective than top-over lashing.

What effective friction coefficient is expected on the route? If $\mu_{eff} < 0{,}25$, anti-slip mats are mandatory.

Are there sections of the route with a critical loading scenario? If so, the number of lashings is determined from the CLS, and an unscheduled securing check is planned for these sections.

What distinguishes the algorithm from existing industry tables is its link to the conditions of a specific route and its use of the CLS as a risk management tool. The driver or dispatcher receives not an abstract norm but a sequence of actions adapted to the specific transport operation.

9.3. Staff training and internal audit

Training is not an add-on to technical regulation but a condition for it to work. Even the most refined rules remain a formality if the people who load and carry cargo every day do not understand what they mean. Directive (EU) 2022/2561 on the initial qualification and periodic training of drivers includes the ability to ensure cargo safety among the mandatory subjects [12]. For Ukrainian companies, a programme of seven modules with a total of 31 academic hours is proposed (Table 9.3).

Table 9.3 **Staff training programme on cargo securing and cargo integrity**

№	Module topic	Audience	Format	Duration, h	Assessment
1	Physics of loads: why cargo shifts	Drivers, loaders	Practical session with demonstration	4	Test
2	EN 12195-1 and the improved method: logic of the calculation, CLS	Technical staff, dispatchers	Lecture and calculation workshop	6	Calculation exercise
3	Securing methods and choice of equipment	Drivers, loaders	Hands-on practice on a vehicle	8	Practical check
4	Friction, anti-slip mats, lashing angles	Drivers, technical staff	Workshop with measurements	3	Test and practice
5	Seasonal and route risks, cargo integrity in the cross-border corridor	Drivers, dispatchers	Case analysis	4	Case exercises
6	Documentation: calculation sheet, inspection report, recording of pre-failure states	All categories	Workshop	2	Completing documents
7	Internal audit and integrity reliability indicators	Managers, safety department	Seminar, case reviews	4	Case presentation

Source: developed by the authors

The programme increases in complexity step by step and is differentiated by audience. Drivers and loaders need above all practical skills: choosing and

tensioning a lashing correctly and checking it en route. Dispatchers and managers need a systemic understanding in order to plan journeys taking the cargo and route into account. Senior managers need managerial competence: an understanding of the company's obligations, internal audit mechanisms and reliability indicators.

Training without control does not produce a lasting effect. A system of internal securing audit is best built at three levels. The operational level involves checking the securing before each departure (5–10 min, recorded in a checklist). The tactical level covers a monthly check of 10–15 % of journeys against the full list of criteria. The strategic level is an annual comprehensive audit involving an external auditor and calculation of the composite reliability indicator from the accumulated data.

The effectiveness of the audit depends on the reporting culture. Staff will report deviations, such as a loosened lashing found at a parking area, only if such a report leads to the problem being fixed rather than to punishment. For the composite indicator, this is of direct importance: every unreported pre-failure state reduces the actual detection coefficient and distorts the reliability assessment.

9.4. Recommendations for supply chain participants

The recommendations are best grouped by the role of the participant, since each of them controls different stages of the chain and different data sources (Table 6.2).

Cargo owners should formulate their requirements for carriers not only in terms of delivery time and the share of perfect orders, but in terms of a target level of the composite indicator I^* and a minimum acceptable level I_{min} under unfavourable conditions that correspond to the value and sensitivity of the cargo. For perishable cargo, contracts should include requirements for pre-cooling and temperature control at handover to the carrier, since this stage is the consignor's responsibility. For cargo loaded by the consignor, the contract should specify who calculates and performs the securing and by which method. For non-perishable cargo with low direct losses, the results of Chapter 8 caution against abandoning monitoring solely on the basis of a traditional economic calculation if the consignee requires a high level of reliability.

Carriers should regard securing by the improved method as a basic measure for packaged general cargo. For such cargo, it pays for itself through

reduced direct losses and has the highest specific effectiveness. The second basic measure is online monitoring with a response procedure: it increases the detection component for any cargo and creates the data without which the other components cannot be calculated. Transport operations with a high risk of theft and long waiting times require parking to be planned with the network of secure sites in mind. The minimum condition for applying the method is a consignment register recording failures by type (Table 2.4) and pre-failure states, including the results of en-route securing checks.

Freight forwarders and logistics operators organising the transport of perishable cargo should coordinate the loading schedule with the electronic queue, using the rule that keeps a place for cargo requiring special storage conditions. In the example considered, this measure had the highest specific effectiveness. Transport options should be compared across several scenarios of border conditions using model (8.3), which guards against decisions that are optimal on average but vulnerable to disruptions.

For the authorities responsible for crossing points, the results show that border waiting time causes not only economic costs but also cargo losses. Extending priority clearance for cargo requiring special storage conditions and developing secure parking near crossing points can be regarded as measures that increase the reliability of the whole corridor. Their effect can be assessed using the proposed indicator.

Practical application of the composite indicator involves a gradual transition from predictive to actual mode. At the first stage, the chain participants set the required parameters and apply the method in predictive mode to compare alternatives, as was done in Chapter 8. At the second stage, once a consignment register covering at least 12 months has been accumulated, the components K_T, K_S and K_D are determined from actual data, and the weights from the results of an extended expert survey. At the third stage, the indicator is used for regular reliability monitoring and for assessing the effect of the measures introduced.

9.5. Proposals for public regulation

The analysis in Chapter 1 and the results of Chapters 4–5 provide grounds for three proposals on public regulation.

The first proposal is to establish the calculation method as the recommended way of confirming that securing is sufficient. This could be a methodological document of the central executive authority for transport, based

on EN 12195-1 and taking into account the refinements for roads with a degraded surface. Such a document would turn the general requirement of the Road Traffic Rules into a verifiable procedure.

The second proposal is to introduce the securing calculation sheet as a recommended, and later mandatory, element of the transport documentation for heavy goods vehicles. The sheet does not require complex calculations during the journey. It records the securing method, the number and type of lashings and the friction coefficient adopted, and allows the inspector to compare the actual securing with the planned one.

The third proposal concerns training: including cargo securing and cargo integrity in the initial and periodic training programmes for drivers of categories C and CE in line with the approaches of Directive (EU) 2022/2561, and giving companies, including small ones, access to the text of the standard and to methodological materials.

9.6. Directions for further research

The results of the monograph were obtained in model calculations, so the main direction of further work is their empirical verification. Five tasks can be identified.

Field measurements to calibrate the securing method. Monitoring of real journeys is needed, measuring lashing tension before and after characteristic sections of the route, cargo accelerations and the friction coefficient for different surface conditions. These data will make it possible to refine the coefficients k_c, k_u, k_w, k_t, k_f and the parameters of the logistic relationship (5.4). The methodological basis for such measurements using MEMS sensors has already been developed [25, 33].

Actual data on integrity failures in the corridor. Consignment registers of carriers in the corridor covering at least 12 months need to be accumulated, and an extended expert survey of cargo owners, carriers and insurers should be conducted to refine the weights.

Digital tool. The improved securing method and the calculation of the composite indicator should be implemented as a web service or mobile application. It should generate a securing plan within a few minutes from the mass, type of cargo, surface materials and route, and maintain a register of pre-failure states. Integration with tension sensors that transmit data to the vehicle's on-board system is a promising option.

Legal models of liability. A comparative study of how responsibility for securing is divided between the driver, the carrier and the consignor in EU states will make it possible to identify the model best suited for adoption in Ukraine.

Extending the method. The composite indicator should be tested on multimodal chains and on other cross-border corridors of the EU external border, and for other types of cargo, in particular pharmaceuticals and dangerous goods.

9.7. Digital tool: functional requirements

Both methods proposed in the monograph require calculations that are inconvenient to perform by hand in practice. A driver will not calculate the effective friction coefficient by formula (4.8) before a journey, and a dispatcher will not run a statistical simulation to compare chain variants. A digital tool is therefore a condition for widespread implementation. Its functional requirements are set out below. They can serve as terms of reference for developing a web service or mobile application.

The tool is best built from three modules corresponding to three levels of users (Table 9.4).

The securing calculation module must work offline, since a connection is not always available at the loading site. The interface should be designed for the driver: selection of the surface material and cargo type from a list, entry of mass and dimensions, and selection of season and route type.

The calculation by formulas (4.4)–(4.8) requires few computing resources and is performed instantly.

The result is presented as a simple diagram showing the number of lashings, their angles and positions, and as a calculation sheet that can be printed or sent electronically together with the e-CMR. For the company's typical loads, the sheets are stored in a library and do not need to be recalculated.

The consignment register module is the basis for reliability assessment. Its structure is given in Appendix D. The most important requirement is that all events be linked to the consignment through a common identifier and to the stage of the carriage process. A failure detected at acceptance can then be attributed retrospectively, using monitoring data, to the stage at which the deviation began. The module must accept data from different sources: manual entry of reports, import of temperature logger files and data exchange with the carrier's telematics platform.

Table 9.4 **Modules of the digital tool and their functions**

Module	Users	Main functions	Input data	Output
1. Securing calculation	Technical staff, drivers, loaders	Calculation of the number of lashings by the algorithm in Table 4.3; tipping check; generation of the calculation sheet	Cargo mass and dimensions, surface materials, body type and condition, lashing equipment, season, route type	Securing plan and number of lashings, stability margin, sheet in PDF format
2. Consignment register	Dispatchers, safety department	Maintaining the register of consignments, failures and pre-failure states; import of telematics, logger and queue data	Consignment note number, dates, stage events, reports, claims	Structured data set for calculating the indicator
3. Reliability assessment	Managers, logistics managers, cargo owners	Calculation of the components and the composite indicator, diagnostic decomposition, selection of measures by model (8.3)	Consignment register, required parameters, weights, list of measures and their costs	Indicator value and reliability level, contributions of components and stages, recommended combination of measures

Source: developed by the authors

The reliability assessment module implements the calculations of Chapter 7. It must work in two modes. In actual mode, the components are calculated from the consignment register for a selected period. In predictive mode, the user sets the parameters of the chain and scenarios, and the module performs a statistical simulation, as in Chapter 8. A Python implementation of the main calculations is given in Appendix G and can be used as a prototype.

Separate requirements concern data quality and information security. Data on consignments, cargo value and claims are commercially sensitive.

The tool must therefore provide access control: the carrier sees its own data, the cargo owner sees data on its own consignments, and summary indicators may be passed to other chain participants only by agreement. For assessing the reliability of a whole corridor, for example by the authorities responsible for crossing points, anonymised aggregated data are sufficient.

9.8. Use of the results in education

As shown in Chapter 1, the cargo securing problem is not only technical but also a matter of human resources. The results of the study should therefore also be used in training specialists. In higher education institutions that train specialists in Automotive Transport, cargo securing is usually covered briefly, at the level of general requirements, within courses on the organisation of freight transport. The topic of integrity reliability of supply chains is, as a rule, absent from curricula.

It is proposed to introduce separate content modules into bachelor’s and master’s programmes (Table 9.5).

The materials in the appendices are suitable for practical classes. The calculation sheets (Appendix A) and checklists (Appendix B) can be used as forms for laboratory work. The expert survey questionnaire (Appendix C) allows students to determine the component weights themselves and compare them between groups. The program code (Appendix G) can serve as the basis for laboratory work on simulation.

Table 9.5 **Content modules for educational programmes in Automotive Transport**

Level	Module	Content	Practical classes	Learning outcome
Bachelor's	Cargo securing safety	Forces acting on cargo; requirements of EN 12195-1; securing methods; effective friction coefficient; lashing angle; tipping check	Securing calculation for three typical loads; preparing a calculation sheet; practical work with lashing equipment	Ability to calculate and perform the securing of a typical load and complete the documentation
Bachelor's	Documenting the condition of cargo	Reservations under the CMR; acceptance reports; e-CMR; consignment register	Completing a consignment note with reservations; case analysis on liability	Ability to record the condition of cargo at the stages of the chain
Master's	Integrity reliability of supply chains	Integrity failure; stage model; composite indicator; fuzzy AHP weights; Harrington scale	Calculating the indicator from register data; determining weights; diagnostic decomposition	Ability to assess chain reliability and identify reserves for improving it

Table continued 9.5

Master's	Selecting reliability improvement measures	Scenario analysis; model for selecting a combination of measures; comparison with the economic criterion	Simulation of a chain in Python; construction of the Pareto set	Ability to justify a combination of measures for a specific chain

Source: developed by the authors

Combining calculation with practice is especially valuable in teaching. A student who has calculated the number of lashings, then tensioned them on a model or a real vehicle and measured the tension, gains the intuitive understanding of load physics that company staff often lack. The laboratory facilities for the module Cargo Securing Safety should therefore be supplemented with a set of lashing equipment, anti-slip mats and a tension gauge.

9.9. Plan for implementing the composite indicator at a company

Implementing the composite indicator at a company requires no less organisational effort than implementing the securing method. The main obstacle is not the complexity of the calculation but the lack of data: most carriers do not systematically record pre-failure states and do not link failures to stages of the carriage process. Implementation is therefore best rolled out gradually (Table 9.6).

The predictive assessment at the second stage produces a result within two to three months of starting work and makes it possible to introduce immediately the measures that are effective under any realistic parameters. As the sensitivity analysis showed (Section 8.9), the composition of the optimal combinations of measures depends little on the exact parameter values, so decisions taken on the basis of the predictive assessment will usually not need to be revised once actual data have been accumulated.

Table 9.6 **Stages of implementing the composite indicator of integrity reliability**

Stage	Duration	Content	Result
1. Preparation	1–2 months	Selecting the chains to be assessed; agreeing the required parameters with cargo owners (P_{int}^{min}, T_{req}); defining stages and data sources	List of chains and parameters; data collection scheme
2. Predictive assessment	1 month	Calculating the indicator in predictive mode for the existing and alternative chain variants	Initial assessment of the reliability level; list of priority measures
3. Data accumulation	12 months	Maintaining the consignment register according to the structure in Appendix D; recording pre-failure states and the results of securing checks	Register sufficient for actual assessment (Table 7.6)
4. Expert determination of weights	in parallel with stage 3	Survey of at least five experts using the questionnaire in Appendix C	Agreed component weights
5. Actual assessment	1 month	Calculating the components from the register; diagnostic decomposition; comparison with the predictive assessment	Substantiated reliability level; refined model parameters
6. Regular monitoring	quarterly	Recalculating the indicator; assessing the effect of the measures introduced	Reliability dynamics; basis for adjusting measures

Source: developed by the authors

During data accumulation, the most important thing is to ensure that pre-failure states are recorded. Failures are recorded without special effort because they lead to claims. Pre-failure states, by contrast, are easily lost: the driver simply tightens a loosened lashing, and nobody writes down a short temperature excursion. This is why the schedule of en-route checks and the reporting culture described in Section 9.3 are not only elements of the safety system but also a condition for measuring reliability.

9.10. Proposals for Ukrainian regulatory documents

The proposals formulated in Section 9.5 are general. Implementing them requires specific amendments to regulatory documents. The authors' proposals on the content of such amendments are set out below. They are not a draft regulatory act and need legal elaboration, but they show which provisions should be supplemented so that the general requirement for secure fastening becomes verifiable.

Rules for the Carriage of Goods by Road. The rules should be supplemented with provisions to the following effect:

the consignor that performs loading ensures that the cargo is stowed and secured in accordance with a calculation performed by a method based on EN 12195-1 or with a standard securing plan for the relevant type of cargo;

before accepting the cargo, the carrier checks that the securing corresponds to the calculation and has the right to refuse cargo whose securing does not correspond to the calculation;

for transport by heavy goods vehicles, the securing calculation sheet is an accompanying document and is presented at the request of enforcement officers;

if the cargo is re-secured after an inspection at the border or en route, a corresponding entry is made in the consignment note or the inspection report.

Procedure for roadside enforcement. A classification of securing deficiencies by severity, similar to that of Directive 2014/47/EU (minor, major, dangerous), should be introduced, with a list of typical deficiencies for each category and the consequences of their detection. For assessing securing during inspections, simplified criteria consistent with the calculation method should be used: the presence of a calculation sheet and the correspondence of the actual securing to it; the number and condition of lashings; how tightly the cargo fits against the stops; and the presence of anti-slip mats where they are provided for.

Driver training. The initial and periodic training programmes for drivers of categories C and CE should include a practical session on cargo securing of at least four hours. It should cover the physics of loads, securing methods, working with the calculation sheet and checking the securing en route (modules 1, 3 and 6 of Table 9.3).

Methodological support. The central executive authority for transport should approve methodological recommendations on calculating cargo securing, containing the calculation algorithm, standard securing plans for common types of cargo and the form of the calculation sheet. The recommendations should be freely available, since paid access to the standard is a real obstacle for small companies.

Importantly, none of these proposals requires significant expenditure from carriers. A calculation sheet is prepared once for a typical load and then only checked. A classification of deficiencies reduces arbitrariness during inspections. Driver training pays for itself, as shown in Chapter 5, through reduced losses. The main condition for implementing the proposals is not funding but coordinated action by the regulator, enforcement bodies and carriers' associations.

Conclusions to Chapter 9

A six-stage roadmap for implementing EN 12195-1 and the improved method at a road haulage company has been developed, together with a simplified three-step model for small companies. The central implementation document is the company standard with calculation sheets for typical loads and a schedule of en-route checks.

A two-level tool for choosing the securing method has been proposed, consisting of a table of typical solutions for eight cargo categories and a four-question decision tree for non-standard situations, linked to route conditions and the critical loading scenario. A seven-module training programme of 31 academic hours, differentiated by audience, and a three-level internal audit system have been developed. Records of en-route securing checks also serve as a data source for the detection component of the composite indicator.

Recommendations have been formulated for cargo owners, carriers, freight forwarders and the authorities responsible for crossing points, together with three proposals on public regulation: a recommended calculation method, a securing calculation sheet in the transport documentation, and inclusion of cargo securing in driver training programmes.

Functional requirements have been defined for a digital tool with three modules: securing calculation, consignment register and reliability assessment. Content modules for bachelor's and master's programmes in Automotive Transport have been proposed, as well as a staged plan for implementing the composite indicator at a company, in which the predictive assessment produces a result within two to three months. Further research should focus primarily on field verification of the model results and on accumulating actual data on integrity failures.

Specific proposals have been formulated on the content of amendments to the rules for the carriage of goods, the roadside enforcement procedure, driver training programmes and methodological support, which make it possible to turn the general requirement for secure fastening into a verifiable procedure without significant costs for carriers.

GENERAL CONCLUSIONS

The monograph addresses the scientific task of developing the scientific and methodological foundations for ensuring cargo integrity in road freight transport. These foundations link the level of the individual load unit on the vehicle with the level of the supply chain. The main results are as follows.

Cargo securing safety regulation in the EU follows a three-tier model: Union acts lay down mandatory requirements and roadside enforcement procedures, UNECE instruments ensure international legal compatibility, and EN 12195-1 turns the requirement for secure fastening into a calculation procedure. The effectiveness of the model depends on the links between the tiers. Ukrainian regulation contains a general requirement for secure fastening but does not establish a method for checking compliance with it. The harmonisation problems have been grouped into regulatory and technical, institutional and behavioural inconsistencies.

Cargo integrity has been substantiated as a separate dimension of supply chain reliability. The concepts of preservation (activity), integrity (state), loss of integrity (event) and integrity reliability (property of the system) have been distinguished. The concept of an integrity failure tied to each act of handover has been introduced, together with a classification of failures that includes a pre-failure state. It has been shown that common performance indicators (OTIF, SCOR perfect order fulfilment) are binary and do not reflect the severity, frequency and location of failures, the chain's ability to limit their consequences or its sensitivity to disruptions.

Hazardous driving situations and the causes of cargo shifting have been systematised. The tipping stability condition has been refined ($b/(2h_c) > c$), and it has been shown that the no-sliding condition under combined loading is stricter than the axis-by-axis check. For a 5 t load, moving from a friction coefficient of 0,2 to 0,6 reduces the required number of top-over lashings from 19 to 3. A model assessment of pretension loss while driving justified the first securing check after 25–30 km on a road in poor condition.

An improved method for calculating cargo securing has been developed. It is based on the concept of a critical loading scenario and the stability margin Z with a required value of 1,25 for roads with a degraded surface. It includes an effective friction coefficient, coefficients of cyclic wear and uneven pretension, and a reserve lashing. The optimum angle of a direct lashing $\alpha_{opt} = \text{arctg}\mu$ has been

obtained, and a range of 20–35° is recommended. The method has been extended to blocking and combined arrangements and supplemented with a check of body strength.

A computational experiment on six model scenarios showed that securing determined by the standard axis-by-axis procedure with the tabulated friction coefficient has a stability margin below one under real conditions in five scenarios (the lowest values being 0,64–0,70). The improved method ensures a margin of at least 1,25 in all scenarios and does not change the result under favourable conditions. For a model company, implementation of the method pays back in less than four months even if the modelled losses are overstated twentyfold. The sensitivity analysis showed that the calculation result depends most on the pretension non-uniformity coefficient and the required margin and, among technical characteristics, on the lashing capacity of the equipment.

The cross-border road corridor on the Polish–Ukrainian border has been described as an environment in which integrity failures arise. The carriage process has been broken down into seven stages, divided into operational and time-dependent ones. External disruptions in 2022–2026 have been systematised into four groups, and it has been shown that they act by lengthening the time-dependent stages and through the direct removal or destruction of cargo.

A composite indicator of integrity-oriented supply chain reliability has been developed from five components: probability, regularity, severity, detection and response, and resilience. The failure probability at the time-dependent stages is determined by an exponential model with an equivalent duration that takes into account the temperature profile of perishable cargo. The quality of securing is taken into account through the rate of securing loosening at the driving stages. The weights are determined by the fuzzy analytic hierarchy process using geometric means. Aggregation is performed by the weighted geometric mean, and interpretation by Harrington's desirability scale.

Testing of the indicator by statistical simulation on a route from Zhytomyr Oblast to Wrocław showed that it distinguishes between chains that the perfect order fulfilment metric regards as identical. With almost the same value of that metric (0,951 and 0,955), the chains carrying chilled berries without and with monitoring obtained scores of 0,655 and 0.818. The indicator responds to external disruptions: in the blockade scenario it falls to 0,262 and 0,479 respectively. The main conclusions are robust to variation of the weights, and the composition of the optimal combinations of measures is robust to the probability of a blockade and the cost of monitoring.

A model has been proposed for selecting a combination of measures that minimises expected costs subject to constraints on the expected level of reliability and on the minimum level in the most unfavourable scenario. For perishable products, the optimal combination is online monitoring, pre-cooling and priority queue registration, and its economic effect is close to the maximum. For non-perishable products, securing by the improved method is the only measure that pays for itself through reduced direct losses, and it has the highest specific effectiveness. This result links the two parts of the study: improving securing at the vehicle level is a justified measure for increasing reliability at the supply chain level.

Practical implementation tools have been developed: a roadmap for implementing EN 12195-1 at a company, a tool for choosing the securing method, a staff training programme of 31 academic hours and a three-level internal audit system. Recommendations for supply chain participants and proposals on public regulation have been formulated.

The numerical results of Chapters 5 and 8 were obtained in model calculations based on scenario assumptions. They confirm the workability and properties of the proposed methods; for practical decisions, the model parameters must be replaced with actual company data. Further research should be directed at field measurements to calibrate the securing method, accumulation of actual data on integrity failures in the corridor, development of a digital tool and extension of the method to multimodal chains.

The results of the monograph can be used by road haulage companies when developing internal standards and training staff, by cargo owners and freight forwarders when formulating requirements for carriers and choosing how to organise transport, by public regulators when preparing regulatory and methodological documents, and by higher education institutions in training specialists in Automotive Transport and related fields.

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APPENDIX A.

CARGO SECURING CALCULATION SHEET

The calculation sheet is the main document confirming that the securing of a particular load is sufficient. It is prepared by a technical employee of the company using the algorithm in Table 4.3 for each typical load or for each non-standard transport operation. The driver carries a copy of the sheet during the journey. The form of the sheet is given in Table A.1, and a completed example for a steel coil in winter conditions (Section 4.6.2) in Table A.2.

Table A.1 **Form of the cargo securing calculation sheet**

Section	Field	Value
General data	Company, sheet number, date of preparation	
	Name of cargo, type of load unit	
	Mass m, kg; dimensions (length × width × height), m	
	Height of centre of mass h_c, m; base width b in the tipping direction, m	
	Material of the cargo's bottom surface	
Vehicle	Body type; strength certificate; body code (EN 12642)	
	Deck material and condition	
	Number and capacity of lashing points	
Lashing equipment	Type (web, chain, wire rope); LC, kN; standard tension force STF, kN	
	Service life N_{max}; cycles used N	
	Anti-slip mats (yes/no), type	
Transport conditions	Season; forecast surface condition (dry, damp, snow, ice)	
	Route type; sections with a damaged surface	
	Critical loading scenario: c_x; c_y	
	CLS sections on the route (name, kilometre)	
Calculation	μ_b; k_w; k_t; k_f; μ_{eff}	
	Tipping check: $b/(2h_c)$ compared with c_y	
	Lashing angle α, deg.; k_c; k_u	
	Effective force of one lashing F_e, kN	
	Resultant inertial force, kN; friction force, kN	

	Design number of lashings; with reserve	
	Stability margin Z	
Securing plan	Securing method (top-over, direct, blocking, combined); positions of lashings	
En-route checks	First check after ___ km; further checks; checks on CLS sections	
Signatures	Prepared by (position, name); checked by; driver informed	

Source: developed by the authors

Table A.2 **Example of a completed calculation sheet (steel coil, winter)**

Section	Field	Value
General data	Name of cargo	Cold-rolled steel coil in a cradle
	Mass, dimensions	8 000 kg; diameter 1,4 m, width 1,2 m
	Material of bottom surface	Steel (via a timber cradle)
Vehicle	Body type	Flatbed semi-trailer with a timber deck, no body strength certificate
	Deck condition	Fair
	Lashing points	2 × 8, capacity 4 000 daN each
Lashing equipment	Type and characteristics	Man-made fibre webs, LC 2 500 daN, STF 400 daN
	Service life and use	N_{max} = 100 cycles, N = 50
	Anti-slip mats	No (variant without mats)
Transport conditions	Season and surface condition	Winter, wet snow, –3 °C
	Route	Highway with sections of damaged surface
	CLS	c_x = 0,8; c_y = 0,35
Calculation	Friction	μ_b = 0,35; k_w = 0,7; k_t = 0,9; k_f = 0,9; μ_{eff} = 0,198
	Tipping	Coil in a cradle, not checked
	Angle and coefficients	α = 30°; k_c = 1,075; k_u = 0,85

	F_e	17,12 kN
	Forces	Resultant inertial force 68,53 kN; friction force 15,57 kN
	Number of lashings	Design 5; with reserve 6
	Stability margin	Z = 1,48 (without the reserve lashing)
Securing plan	Method	Direct lashing: 3 lashings on each side of the coil, crossed forward and backward
En-route checks	Checks	First after 25–30 km; then every 3 h of driving and before sections with a damaged surface

Source: developed by the authors

Note to the example. In the variant with anti-slip mats (μ_b = 0,6, k_w = 0,85), the design number falls to three lashings, and with the reserve to four (Section 4.6.2).

APPENDIX B.

DRIVER CHECKLIST AND SECURING INSPECTION REPORT

The driver fills in the checklist at every loading before departure (Table B.1).

The en-route securing inspection report (Table B.2) is completed at every check. The entries in the report are a source of data on pre-failure states for the consignment register (Appendix D).

Table B.1 **Driver checklist before departure**

№	What to check	Yes	No	Note
1	There is a calculation sheet for this load, and the actual load corresponds to it			
2	The deck is clean, free of snow, ice, oil and debris			
3	Anti-slip mats have been laid if the sheet provides for them			
4	The cargo fits tightly against the headboard or stops; gaps are filled			
5	The number of lashings is not less than in the sheet			
6	Lashings have legible labels, with no cuts, knots or damaged stitching			
7	Lashing angles correspond to the sheet (approximately 20–35° for direct lashing)			
8	Lashings are tensioned; sharp edges of the cargo are protected by corner protectors			
9	Lashing points are sound; lashings are attached only to designated points			
10	Tall load units have been checked for tipping and secured accordingly			
11	Sideboards, curtains and doors are closed and locked; a seal has been fitted (if required)			
12	The CLS sections on the route and the check points are known			

Source: developed by the authors

Table B.2 **En-route cargo securing inspection report**

Field	Entry
Consignment note (e-CMR) number, date	
Place of check (road, kilometre, parking area)	
Distance travelled since loading, km	
Reason for the check (scheduled, CLS section, after harsh braking, other)	
Condition of lashings (tensioned / loosened; number loosened)	
Signs of cargo displacement (none / up to 5 cm / more than 5 cm)	
Condition of cargo and packaging (unchanged / damage found)	
Action taken (retensioned, lashings added, cargo restowed, other)	
Time spent on the check, min	
Is there a pre-failure state (yes/no); did it turn into a failure (yes/no)	
Driver's signature	

Source: developed by the authors

APPENDIX C.

EXPERT SURVEY QUESTIONNAIRE FOR DETERMINING COMPONENT WEIGHTS

The questionnaire is intended for experts from among cargo owners, carriers, freight forwarders and insurers. Its results are used to determine the weights of the components of the composite indicator according to the procedure in Section 7.3.

Information about the expert. Organisation; position; experience in transport, years; type of cargo for which the assessment is given; main transport route.

Instructions. For each pair of components, choose which of them is more important for assessing the reliability of the supply chain for the specified type of cargo, and by how much. Use the scale in Table C.1. If both components are equally important, put a dash in the third column and write “equal” in the fourth. The content of the components is given in Table C.2.

Table C.1 **Linguistic scale of pairwise comparisons**

Rating	Meaning	Triangular fuzzy number
Equal importance	Both components are equally important	(1, 1, 1)
Weak preference	Experience and judgement slightly favour one component	(1, 2, 3)
Moderate preference	Experience and judgement clearly favour one component	(2, 3, 4)
Between moderate and strong	Intermediate judgement	(3, 4, 5)
Strong preference	The preference for one component is evident	(4, 5, 6)

Source: developed by the authors

Table C.2 **Components of the composite indicator (reference for the expert)**

Component	What it reflects
K_P – probability	How rarely the cargo suffers any integrity failure
K_T – regularity	Whether there are series of failures following one another; frequency of claims
K_S – severity	What share of the cargo value is retained in the event of a failure
K_D – detection and response	Whether the chain can notice a violation before the cargo is spoiled and correct it
K_R – resilience	How much reliability deteriorates when waiting at the border becomes long

Source: developed by the authors

Table C.3 **Pairwise comparison form**

№	Pair of components	More important component (specify)	Degree of preference (equal, weak, moderate, between moderate and strong, strong)
1	$K_P - K_T$		
2	$K_P - K_S$		
3	$K_P - K_D$		
4	$K_P - K_R$		
5	$K_T - K_S$		
6	$K_T - K_D$		
7	$K_T - K_R$		
8	$K_S - K_D$		
9	$K_S - K_R$		
10	$K_D - K_R$		

Source: developed by the authors

Processing the results. For each expert, the matrix of mean values is constructed and the consistency ratio CR is checked. If CR > 0,10, the questionnaire is returned to the expert with a request to revise the most inconsistent judgements. The consistent matrices are aggregated by element-wise geometric averaging, after which the weights are calculated by formula (7.11) and the procedure of Section 7.3.

APPENDIX D.

STRUCTURE OF THE CONSIGNMENT REGISTER

The consignment register is the main data source for calculating the components of the composite indicator in actual mode. It consists of three linked tables: consignments, events and failures. Their fields are given in Tables D.1–D.3.

Table D.1 **Table "Consignments"**

Field	Data type	Content	Use
Consignment ID	Text	CMR or e-CMR consignment note number	Key for linking tables
Date and time of taking over the cargo	Date/time	End of stage E1	Ordering consignments for K_T
Date and time of delivery	Date/time	End of stage E7	Transport duration
Route, crossing point	Text	Route identifier	Grouping for assessment
Type of cargo	Lookup list	Perishable / non-perishable / other	Choice of weights and required parameters
Cargo value V, UAH or EUR	Number	From accompanying documents	Calculation of K_S
Securing calculation sheet number	Text	Reference to the sheet (Appendix A)	Link to the securing method
Recommended temperature θ_{ref}, °C	Number	For perishable cargo	Calculation of t^{eq}
Duration of stages E1–E7, h	Number (7 fields)	From telematics and queue data	Calculation of K_P, K_R
Measures applied (M1–M5)	Multiple choice	Which measures were in force on the journey	Assessing the effect of measures

Source: developed by the authors

Table D.2 **Table "Events" (pre-failure states)**

Field	Data type	Content	Use
Event ID	Text	Unique number	–
Consignment ID	Text	Link to the "Consignments" table	–
Stage	Lookup list	E1–E7	Localisation of risk
Event type	Lookup list	Temperature excursion, loosened securing, broken seal, attempted access, excessive dwell time, other	Structure of pre-failure states
Start time and duration	Date/time, number	From logger, telematics or report	Calculation of t^{eq}
Detection method	Lookup list	Monitoring, driver during a check, retrospectively after a failure	Calculation of n_{pf}, n_{det}
Action taken and response time	Text, number	What was done and when	Calculation of r
Turned into a failure	Yes/no	Link to the "Failures" table	Calculation of n_{tr}

Source: developed by the authors

Table D.3 **Table "Failures"**

Field	Data type	Content	Use
Failure ID	Text	Unique number	–
Consignment ID	Text	Link to the "Consignments" table	–
Failure type	Lookup list	Total, partial quantitative, qualitative apparent, qualitative hidden (Table 2.4)	Classification
Stage of detection	Lookup list	Mostly E7 or after delivery	–
Stage of origin	Lookup list	Established retrospectively	Decomposition by stages
Cause	Lookup list	By the groups of Tables 3.4 and 6.3	Selection of measures
Value lost ΔV	Number	From the discrepancy report or claim	Calculation of K_S
Supporting document	Text	Reservation, report, claim	Verifiability of the entry

Source: developed by the authors

The minimum size of the register for actual assessment is set in Table 7.6: at least 200 consignments over a period of at least 12 months and at least five failures for calculating the regularity component.

APPENDIX E.

FULL SIMULATION RESULTS FOR COMBINATIONS OF MEASURES

This appendix gives the results for all combinations of measures considered in Section 8.8. The combinations are ordered by increasing expected cost. “Yes” in the last column means that the combination is Pareto-optimal with respect to expected costs and the expected value of the indicator.

Table E.1 **Results for perishable products (32 combinations)**

Combination	Costs, EUR per journey	$\bar{I}$	I, S1	I, S2	I, S3	Losses, EUR per journey	ΔE, EUR per journey	Pareto
No measures	0,0	0,609	0,650	0,565	0,262	635,2	–	yes
M5	4,0	0,639	0,663	0,615	0,414	494,6	+136,6	yes
M4	10,0	0,623	0,662	0,582	0,283	607,2	+18,0	
M3	14,0	0,637	0,669	0,603	0,345	528,9	+92,3	
M4 + M5	14,0	0,650	0,672	0,632	0,429	466,5	+154,7	yes
M2 + M5	14,3	0,640	0,664	0,618	0,421	487,3	+133,6	
M2	17,1	0,616	0,655	0,573	0,278	623,9	–5,8	
M3 + M5	18,0	0,660	0,678	0,648	0,467	408,6	+208,6	yes
M3 + M4	24,0	0,646	0,677	0,617	0,357	500,8	+110,4	
M2 + M4 + M5	24,3	0,652	0,673	0,634	0,435	459,2	+151,7	
M2 + M4	27,1	0,626	0,664	0,585	0,296	595,9	+12,2	
M3 + M4 + M5	28,0	0,668	0,686	0,655	0,478	380,5	+226,7	yes
M2 + M3 + M5	28,3	0,662	0,679	0,651	0,473	401,3	+205,7	
M2 + M3	31,1	0,639	0,671	0,606	0,356	517,4	+86,7	
M1	32,0	0,783	0,819	0,744	0,474	484,9	+118,3	yes
M1 + M5	36,0	0,808	0,828	0,791	0,608	405,9	+193,3	yes
M2 + M3 + M4 + M5	38,3	0,669	0,687	0,657	0,484	373,2	+223,8	
M2 + M3 + M4	41,1	0,649	0,679	0,620	0,372	489,4	+104,7	
M1 + M4	42,0	0,789	0,824	0,754	0,484	472,6	+120,6	
M1 + M3	46,0	0,811	0,837	0,787	0,559	397,7	+191,5	
M1 + M4 + M5	46,0	0,814	0,833	0,801	0,615	393,6	+195,6	yes

M1 + M2 + M5	46,3	0,808	0,828	0,792	0,612	402,8	+186,1	
M1 + M2	49,1	0,785	0,820	0,751	0,481	480,1	+106,0	
M1 + M3 + M5	50,0	0,830	0,845	0,819	0,666	329,8	+255,4	yes
M1 + M3 + M4	56,0	0,816	0,841	0,796	0,567	385,5	+193,7	
M1 + M2 + M4 + M5	56,3	0,815	0,833	0,802	0,626	390,5	+188,4	
M1 + M2 + M4	59,1	0,792	0,824	0,762	0,491	467,9	+108,2	
M1 + M3 + M4 + M5	60,0	0,834	0,849	0,823	0,678	317,6	+257,7	yes
M1 + M2 + M3 + M5	60,3	0,831	0,846	0,820	0,670	326,8	+248,2	
M1 + M2 + M3	63,1	0,813	0,838	0,794	0,565	392,9	+179,2	
M1 + M2 + M3 + M4 + M5	70,3	0,835	0,850	0,824	0,682	314,5	+250,4	yes
M1 + M2 + M3 + M4	73,1	0,817	0,842	0,798	0,573	380,7	+181,4	

Source: calculated by the authors

Table E.2 **Results for non-perishable products (8 combinations)**

Combination	Costs, EUR per journey	$\bar{I}$	I, S1	I, S2	I, S3	Losses, EUR per journey	ΔE, EUR per journey	Pareto
No measures	0,0	0,592	0,601	0,583	0,513	48,2	–	yes
M4	10,0	0,680	0,695	0,663	0,562	30,0	+8,2	yes
M2	17,1	0,606	0,609	0,603	0,580	40,9	–9,8	
M2 + M4	27,1	0,700	0,704	0,697	0,661	22,7	–1,6	yes
M1	32,0	0,843	0,850	0,838	0,785	26,1	–9,9	yes
M1 + M4	42,0	0,897	0,902	0,891	0,854	17,1	–10,9	yes
M1 + M2	49,1	0,853	0,855	0,850	0,835	23,2	–24,1	
M1 + M2 + M4	59,1	0,905	0,907	0,904	0,891	14,2	–25,1	yes

Source: calculated by the authors

APPENDIX F.

STEP-BY-STEP EXAMPLE OF CALCULATING THE COMPOSITE INDICATOR

The example illustrates the calculation of the indicator in actual mode using hypothetical consignment register data. All values are for training purposes and do not relate to any particular company.

Input data. A chain carrying chilled products with a recommended temperature of 2 °C. Over 12 months, 260 consignments were made. Required parameters: P_{int}^{min} = 0,95; T_{req} = 40 consignments. The component weights are taken from Table 7.4.

Step 1. Stage failure probabilities. For the operational stages, from the register statistics: at E1 there are two risk sources with probabilities 0,003 and 0,001, so by formula (7.1) q_1 = 1 – 0,997 · 0,999 = 0.003997. At E4, q_4 = 0.002. At E7 there are two sources, 0,002 and 0,001, so q_7 = 0.002998.

For the time-dependent stages: at E2 the rate is 0,00025 h^{-1} and the duration 8 h, q_2 = 1 – exp(–0,002) = 0.001998. At E5 the rate is 0,0003 h^{-1} and the duration 6 h, q_5 = 0.001798. At E3, according to the logger, the cargo spent 4 h at 2 °C and 1,5 h at 9 °C. By formula (7.3) with Q_{10} = 2,5, the equivalent duration is 4 + 1,5 · 2,5^0,7 = 4 + 2,849 = 6,849 h. With a rate of 0,0004 h^{-1}, we obtain q_3 = 0.002736.

Step 2. Probability component. By formula (7.4), P_{int} = 0,996003 · 0,998002 · 0,997264 · 0,998 · 0,998202 · 0,997002 = 0.98457. By formula (7.5), K_P = (0,98457 – 0,95) / 0,05 = 0.691.

Step 3. Regularity component. Failures were recorded in consignments No. 23, 61, 88, 97, 140, 171, 205, 214 and 249. The intervals between them are 38, 27, 9, 43, 31, 34, 9 and 35 consignments. The median of the eight intervals is (31 + 34) / 2 = 32.5. By formula (7.6), K_T = 32,5 / 40 = 0.813.

Step 4. Severity component. The shares of value lost in the nine failures are 0,05; 0,12; 0,03; 1,00; 0,08; 0,20; 0,04; 0,35; 0.06. The mean is 0,214, so K_S = 1 – 0,214 = 0.786. A single total failure accounts for more than half of the mean share of losses.

Step 5. Detection and response component. The register records 24 pre-failure states, of which 17 were detected during carriage, and 3 of those detected turned into failures despite intervention. Then d = 17/24 = 0,708, r = 1 – 3/17 = 0,824, K_D = 0.583.

Step 6. Resilience component. According to queue data, the median waiting time is 6 h, σ = 1.0. By formula (7.9), t_{95} = 6 · e^1,645 = 31,09 h. By the simplified formula of Section 7.2.6 with a rate of 0,0004 h^{-1}, K_R = exp(–0,0004 · 25,09) = 0.990.

Step 7. Aggregation. By formula (7.12) with weights 0,349; 0,121; 0,185; 0,160; 0,185:

I_{int} = 0,691^0,349 · 0,813^0,121 · 0,786^0,185 · 0,583^0,160 · 0,990^0,185 = 0,751.

According to Table 7.5, the reliability level is adequate.

Step 8. Diagnostic decomposition. By formula (7.13), the shares of the components in the reliability deficit are: K_P 44,9 %; K_T 8,8 %; K_S 15,6 %; K_D 30,1 %; K_R 0,6 %. The shares of the stages in the total failure probability are: E1 25,8 %; E2 12,9 %; E3 17,6 %; E4 12,9 %; E5 11,6 %; E7 19,3 %.

Conclusion from the example. The main reserves lie in the probability component and the detection component. The largest contribution to the failure probability comes from the loading (E1) and unloading (E7) stages. The priority measures are therefore to improve securing and control during handling and to extend monitoring so that a larger share of pre-failure states is detected in time.

APPENDIX G.

SOFTWARE IMPLEMENTATION OF THE MAIN CALCULATIONS

Below is Python code that implements the calculation of the number of lashings (Chapter 4) and the calculation of the composite indicator from register data (Chapter 7). The code requires no third-party libraries. Running the block of examples at the end reproduces the results of example 4.6.2 (six lashings, stability margin 1,48) and of Appendix F (indicator 0,751, adequate level).

```
import math

G = 9.81  # acceleration due to gravity, m/s2

def mu_eff(mu_b, k_w=1.0, k_t=1.0, k_f=1.0):
    """Effective friction coefficient, formula (4.8)."""
    return mu_b * k_w * k_t * k_f

def k_wear(n_used, n_max, d_max=0.15):
    """Cyclic wear coefficient, formula (4.5)."""
    return 1.0 + (n_used / n_max) * d_max

def lashing_count(m, mu_b, k_w, k_t, k_f, alpha_deg, n_used, n_max,
                  c_x=0.8, c_y=0.0, lc=25.0, k_u=0.85, z_req=1.25, d_max=0.15):
    """Number of direct lashings, formulas (4.4)-(4.7).
    m - mass, kg; lc - lashing capacity, kN."""
    w = m * G / 1000.0                          # weight, kN
    mu = mu_eff(mu_b, k_w, k_t, k_f)
    kc = k_wear(n_used, n_max, d_max)
    f_e = lc * math.cos(math.radians(alpha_deg)) * k_u / kc  # (4.6)
    f_comb = w * math.sqrt(c_x ** 2 + c_y ** 2)         # resultant force
    need = z_req * f_comb - mu * w
    n_design = max(1, math.ceil(need / f_e))
    z = (mu * w + n_design * f_e) / f_comb              # (4.4)
    return {'mu_eff': mu, 'k_c': kc, 'F_e': f_e, 'F_comb': f_comb,
            'n_design': n_design, 'n_total': n_design + 1, 'Z': z}

def tipping_check(m, b, h_c, c_y=0.6):
```

```
    """Tipping stability check, condition (3.3)."""
    ratio = b / (2.0 * h_c)
    return ratio, ratio > c_y

def stage_failure_operational(q_sources):
    """Failure probability at an operational stage, formula (7.1)."""
    p_ok = 1.0
    for q in q_sources:
        p_ok *= 1.0 - q
    return 1.0 - p_ok

def equivalent_time(intervals, theta_r, q10):
    """Equivalent duration, formula (7.3).
    intervals - list of pairs (duration, h; temperature, deg. C)."""
    return sum(dt * q10 ** ((th - theta_r) / 10.0) for dt, th in intervals)

def stage_failure_time(lam, t_eq):
    """Failure probability at a time-dependent stage, formula (7.2)."""
    return 1.0 - math.exp(-lam * t_eq)

def integral_index(q_stages, p_min, failures_idx, t_norm, severities,
                   n_pv, n_det, n_trans, lam3, t50, sigma, weights):
    """Composite indicator of integrity-oriented reliability."""
    p_int = 1.0
    for q in q_stages:
        p_int *= 1.0 - q                          # (7.4)
    k_p = max(0.0, (p_int - p_min) / (1.0 - p_min))       # (7.5)
    gaps = sorted(b - a for a, b in zip(failures_idx, failures_idx[1:]))
    k = len(gaps)
    med = gaps[k // 2] if k % 2 else (gaps[k // 2 - 1] + gaps[k // 2]) / 2
    k_t = min(1.0, med / t_norm)                  # (7.6)
    k_s = 1.0 - sum(severities) / len(severities)       # (7.7)
    d = n_det / n_pv
    r = 1.0 - n_trans / n_det
    k_d = d * r                                   # (7.8)
    t95 = t50 * math.exp(1.645 * sigma)           # (7.9)
    k_r = math.exp(-lam3 * (t95 - t50))           # simplified (7.10)
```

```
        comps = [k_p, k_t, k_s, k_d, k_r]
        index = 1.0
        for kk, ww in zip(comps, weights):
            index *= kk ** ww                       # (7.12)
        deficit = [ww * math.log(kk) / math.log(index) for kk, ww in zip(comps,
weights)]
        return {'P_int': p_int, 'K': comps, 'I': index, 'delta': deficit}

    def level(i):
        """Reliability level on the scale of Table 7.5."""
        if i >= 0.80:
            return 'high'
        if i >= 0.63:
            return 'adequate'
        if i >= 0.37:
            return 'reduced'
        if i >= 0.20:
            return 'low'
        return 'critical'

    if __name__ == '__main__':
        # example 4.6.2: steel coil in winter, without mats
        print(lashing_count(8000, 0.35, 0.7, 0.9, 0.9, 30, 50, 100, c_y=0.35))
        # example from Appendix F
        q = [stage_failure_operational([0.003, 0.001]),
             stage_failure_time(0.00025, 8),
             stage_failure_time(0.0004, equivalent_time([(4, 2), (1.5, 9)], 2, 2.5)),
             0.002,
             stage_failure_time(0.0003, 6),
             stage_failure_operational([0.002, 0.001])]
        res = integral_index(q, 0.95, [23, 61, 88, 97, 140, 171, 205, 214, 249], 40,
                             [0.05, 0.12, 0.03, 1.0, 0.08, 0.20, 0.04, 0.35, 0.06],
                             24, 17, 3, 0.0004, 6, 1.0,
                             [0.349, 0.121, 0.185, 0.160, 0.185])
        print(res, level(res['I']))
```

APPENDIX H.

MODEL STRUCTURE OF A COMPANY STANDARD FOR CARGO SECURING

A company standard for cargo securing (Section 9.1) translates the requirements of EN 12195-1 and of the improved method into the language of a particular company's procedures. The recommended structure of such a document is given below. The company adapts the content of the sections to its fleet, cargo types and routes.

Table H.1 **Recommended structure of a company standard for cargo securing**

№	Section of the standard	Content	Responsible for updating
1	Scope	Types of transport, vehicles and cargo covered by the standard; references to EN 12195-1 and the EU guidelines	Technical manager
2	Terms and definitions	Lashing, lashing capacity, pretension, friction coefficient, stability margin, critical loading scenario, pre-failure state	Technical manager
3	Allocation of duties	Duties of the consignor, driver, dispatcher, technical department and safety department; procedure for agreeing the securing with the consignor	Company director
4	Requirements for vehicles	List of bodies with strength certificates; lashing points and their capacity; deck requirements	Fleet operations department
5	Requirements for lashing equipment	Permitted types; marking; recording of use cycles; discard criteria; storage	Procurement department
6	Calculation method	Algorithm of Table 4.3; adopted values of the coefficients k_u, δ_{max}, k_w, k_t, k_f, Z_{req}; procedure for determining the CLS for the company's routes	Technical department
7	Library of calculation sheets	Sheets for typical loads (form of Appendix A); procedure for preparing sheets for non-standard loads	Technical department

8	Loading and securing procedure	Sequence of actions; load placement taking axle loads into account; use of anti-slip mats; checklist (Appendix B)	Drivers, loaders
9	En-route checks	Frequency of checks according to road condition; checks on CLS sections; inspection report (Appendix B); action if loosening or displacement is found	Drivers, dispatchers
10	Recording and reporting	Maintaining the register of consignments, events and failures (Appendix D); procedure for reporting pre-failure states	Safety department
11	Staff training	Training programme (Table 9.3); frequency; competence assessment	HR department
12	Internal audit	Operational, tactical and strategic audit levels; criteria; documenting the results; corrective action	Safety department
13	Reliability assessment	Procedure for calculating the composite indicator; required parameters for the main chains; frequency	Logistics department
14	Revision of the standard	Grounds for and frequency of revision; procedure for making amendments	Technical manager

Source: developed by the authors

Sections 6, 7 and 9 form the core of the standard. It is they that turn the general requirement that "the load must be securely fastened" into specific actions of the driver and technical staff. Sections 10 and 13 link the securing safety system with the assessment of the integrity reliability of the supply chain: the records kept for checking securing also become input data for calculating the indicator.

Three principles should be followed when developing the standard. First, every requirement must be verifiable: instead of "the load is securely fastened", one should write "the number of lashings is not less than in the calculation sheet". Second, documents should be kept to a minimum: one sheet per typical load, one checklist per loading, one report per en-route check. Third, the standard must be reviewed regularly. A standard that has not been updated for several years no longer matches the real fleet, cargo and routes and becomes a formality.

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CARGO INTEGRITI IN ROAD LOGISTICS

Monograph

ISBN 978-83-66567-74-0

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45-085 Poland, Opole, ul. Niedzialkowskiego 18 tel. 77 402-19-00/01.

NATIONAL UNIVERSITY OF LIFE AND ENVIRONMENTAL SCIENCES OF UKRAINE

THE ACADEMY OF APPLIED SCIENCE
ACADEMY OF MANAGEMENT AND ADMINISTRATION IN OPOLE



ISBN 978-83-66567-74-0