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REVIEW ARTICLE

The Reliability and Integrity of Smart Roads in the Context of Homeland Security and Asset Management

Filippo G. Praticò[1,*], Rosario Fedele[1] and Gianfranco Pellicano[1]

[1] *DIIES Department, University Mediterranea of Reggio Calabria, Reggio Calabria, Via Graziella - Feo di Vito, Reggio Calabria 89100, Italy*

Abstract:

The reliability and integrity of smart roads in the context of homeland security and asset management pertain to different risks and phenomena. Unfortunately, many issues remain unsolved in terms of the relationship between different types of risks (*e.g.*, safety *versus* structural integrity), the impact of information technologies, and the impact of the construction technologies and design options (*e.g.*, viaduct or tunnel). In light of the above, the objectives of this paper were confined to the following: 1) Analysing critical road infrastructures, CRI, in the context of homeland security, asset management and information communication technologies, ICT. 2) Setting up a risk model for CRIs. Three equations were derived. Results demonstrate the complexity of the studied system, where many components interact. Future research will focus on the main criticalities that emerged in the study.

Keywords: Risk, Reliability, Integrity, Transportation infrastructure, Friction, Surface texture.

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1. INTRODUCTION

The reliability and integrity of smart roads in the context of homeland security and asset management pertain to different risks and phenomena. For roads, this includes 1) the decay of functional properties (*e.g.*, friction, drainability, quietness, surface texture, and reflectivity). 2) The decay of mechanistic ones (*e.g.*, moduli, hidden micro-cracks patterns, and granular base drainage). 3) The variation of volumetrics (*e.g.*, clogging phenomena). 4) The failure of different types of road furniture (*e.g.*, traffic barriers, road signs, guideposts, light and utility poles, boundary fences, and raised road markers). 5) Particulate matter generation, accumulation and resuspension. 6) Hazmat resistance. 7) The effectiveness and durability of smart, Internet-of-Things, IoT, and ICT-based solutions for maintenance and rehabilitation (*e.g.*, applicators, strain gauges, cameras, communication protocols and systems, and different types of I2X communication systems, where I2X stands for Infrastructure-to-everything communications). 8) The disruptive failures of hard and soft items (*e.g.*, viaducts, ICT systems). Despite many studies addressing the topics above, unfortunately, the following issues remain unsolved: 1) what is the relationship between the risks that pertain to safety and the ones that refer to a transportation infrastructure's reliability and security in providing a rideable platform? 2) what is the impact that information technologies have in terms of the probabilities and risks related to the use of transportation infrastructure? 3) How can the technologies used to build a transportation infrastructure affect its reliability? These unsolved questions highlight that studies dealing with the complexity above are quite ground-breaking and mainly unaddressed. Consequently, the main objectives of the study described in this paper are:

(1) Setting up a theoretical framework, *i.e.*, a conceptual scheme dealing with the reliability and integrity of roads as critical infrastructures, where risks, causes and remedies are addressed and listed.

(2) Modelling safety-related and security-related probabilities, where hard (*e.g.*, transport infrastructures) and soft components (*e.g.*, Information and Communication Technology, ICT) are merged.

To this end (Fig. **1**), in Task 1 (section 2.1 and Fig. **2**) attention was focused on the analysis of critical infrastructures namely critical road infrastructures, CRI, in Task 2 (section 2.2, and Figs. **3** - **5**) an in-depth analysis of CRI risks was carried out, while in Task 3 (cf. section 2.3), for CRI-related risks, causes and remedies were addressed. Finally, in Task 4 (Section 3 and Fig. **6**), three equations were derived with the aim of quantifying CRI-related risks.

* Address correspondence to this author at the DIIES Department, University Mediterranea of Reggio Calabria, Reggio Calabria, Via Graziella - Feo di Vito, Reggio Calabria 89100, Italy; E-mail: filippo.pratico@unirc.it

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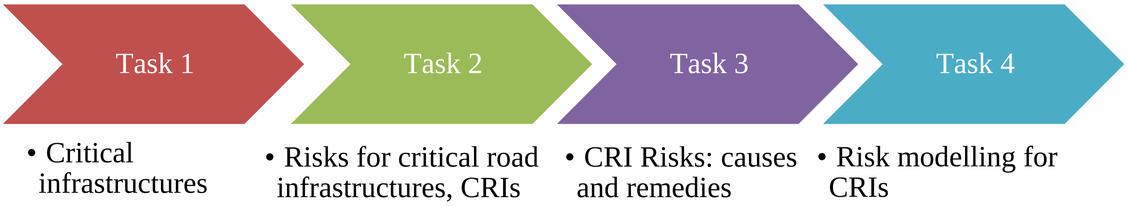


Fig. (1). Tasks.

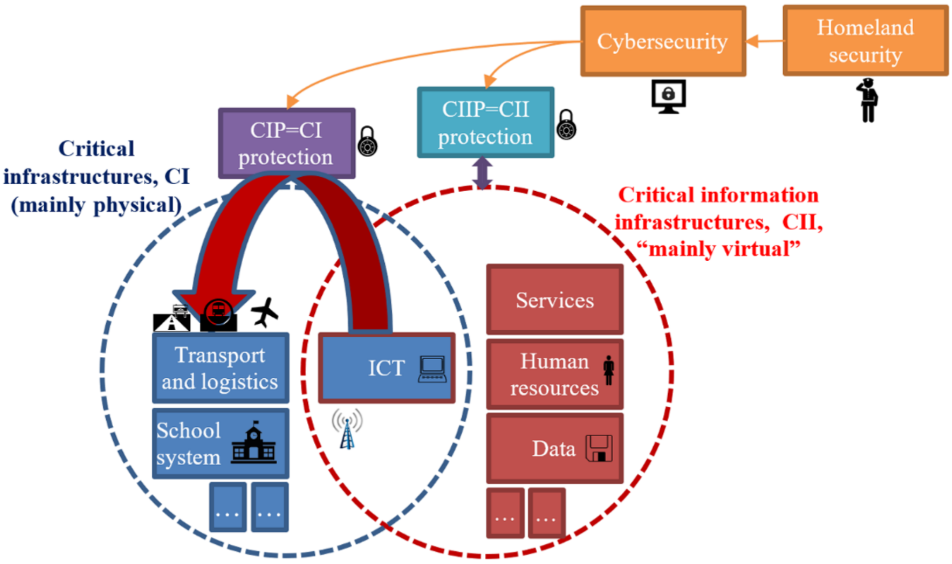


Fig. (2). Infrastructures (left), information infrastructures (right), their criticality and protection (above).

2. ANALYSIS OF INFRASTRUCTURE RISKS

2.1. Infrastructures

As is well known [1], Infrastructure is defined as the physical system of an activity or region and often involves the production of public goods or related production processes. **Critical infrastructures, CIs**, refer to the ones that are essential for the functioning of a society and economy. Examples of critical infrastructures, CIs [2 - 5], include (see Fig. **2**):

- Chemical Sector
- Commercial Facilities Sector
- Communications Sector
- Critical Manufacturing Sector
- Dams Sector
- Defence Industrial Base Sector
- Emergency Services Sector
- Energy Sector
- Financial Services Sector
- Food and Agriculture Sector
- Government Facilities Sector
- Healthcare and Public Health Sector
- Identifying Critical Infrastructure During COVID-19
- **Information Technology Sector**
- Nuclear Reactors, Materials, and Waste Sector
- Sector-Specific Agencies
- **Transportation Systems Sector.**
- Water and Wastewater Systems Sector.

In turn, the Transportation Systems Sector includes:

- Aviation
- **Highway and Motor Carrier (critical road infrastructures, CRI)**
- Maritime Transportation System
- Mass Transit and Passenger Rail sector
- Pipeline Systems
- Freight Rail
- Postal and Shipping.

ICT have a twofold nature: they are both CIs and critical information infrastructures, **CIIs**. They provide **critical infrastructure protection, CIP**, *i.e.*, they are ICT networks that support, link, and enable other CIs.

To this end, it is noted that the European Programme for Critical Infrastructure Protection (EPCIP) has been laid out in EU Directives by the Commission (Commission of the European Communities).

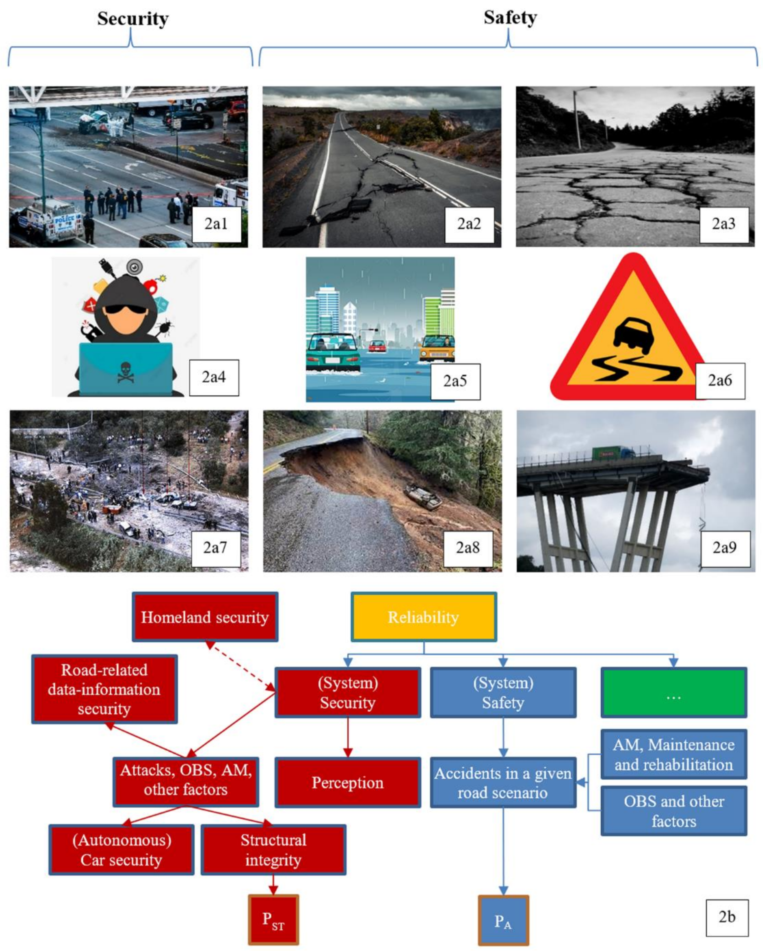
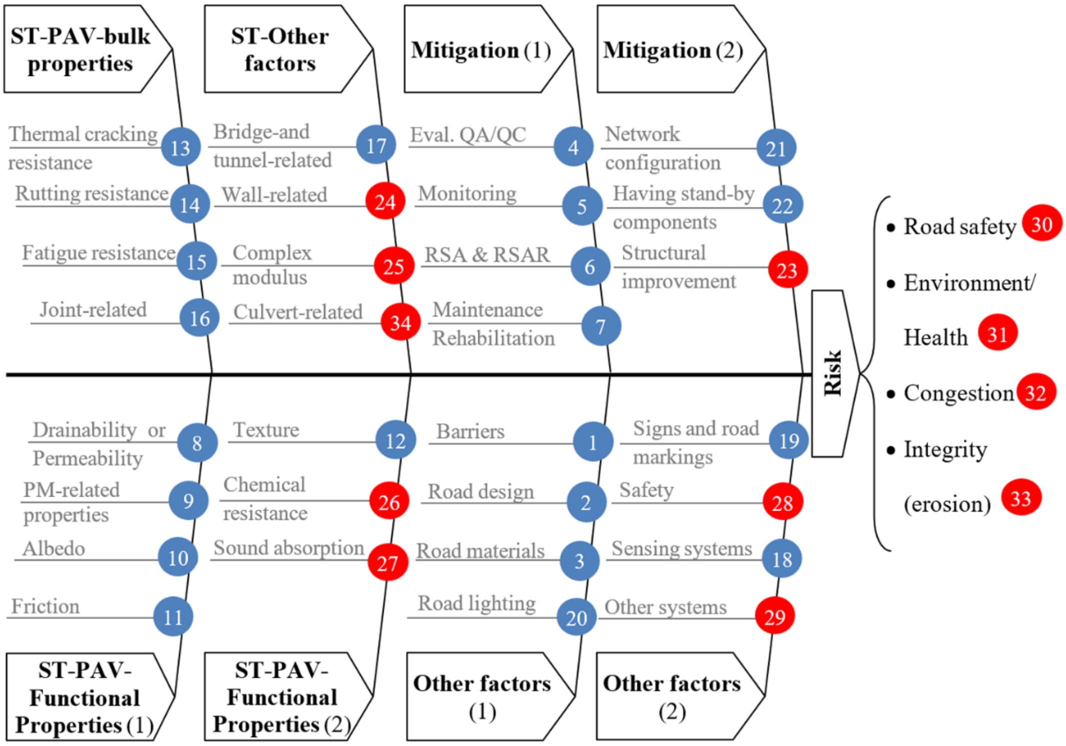


Fig. (3). Examples of risks (**3a**, above) and relationships among safety, security, system, and infrastructure (**3b**, below). Symbols. AM = asset management. OBS = obsolescence. Sources [24–32].

Fig. (4). Risk-related terminology.

CI complexity, interconnectedness and interdependency amplify the concerns related to their protection and to this end, ICT infrastructures can be used to provide critical infrastructure protection as a set of “risk management and operational response activities aimed at improving the security and resiliency” of CIs [2, 6, 7]. From this standpoint, ICT (as systems of software, hardware, and services) help other CIs to be more resilient. Not only does ICT help protect other CIs, in terms of Critical information protection, but additionally ICT itself has to be protected in terms of cybersecurity and **Critical information infrastructure protection, CIIP**. In other words, CIIP refers to the activities aiming at protecting critical information infrastructures (*e.g.*, related to transports, communication, finance, military, and energy) from cyber-attacks [8, 9]. Importantly, computer security (or cybersecurity) addresses both CIIP and CI and is a vital part of Homeland Security.



Symbols. ST=Structures; PAV=Pavements; PM=Pavement Management; Eval.=Evaluation; QA/QC= Quality Assurance/Quality Control; RSA= Road Safety Audit; RSAR=Road Safety Audit Reviews.

Fig. (5). Theoretical framework.

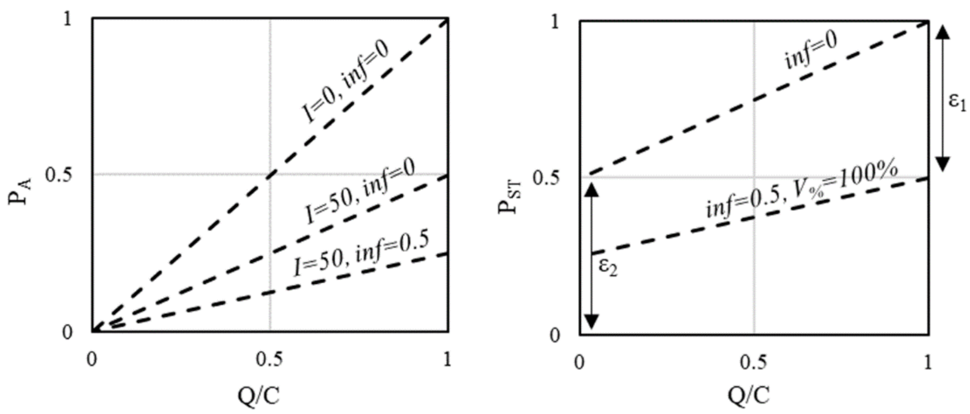


Fig. (6). Parameters influencing P_A (eq. 2) and P_{ST} (eq. 3).

Transportation systems combine elements and their interactions that produce the demand for travel within a given area and the supply of transportation services to satisfy this demand [10]. Supply and demand relate to facilities (transportation infrastructures, *e.g.*, roads, railways, and airports), users, vehicles, and environmental conditions. On the other hand, when it comes to supply, communication networks and transportation infrastructures are becoming more and more synergistic and it seems already difficult to think of several applications (*e.g.*, infrastructure monitoring and autonomous vehicles) without a close relationship and synergy between communication networks and transportation infrastructures. For this reason, the term infrastructure (instead of transportation infrastructure) is sometimes used, where the infrastructure is meant to include communication and transportation "entities".

2.2. Risks

The concept of **risk** [11, 12] related to a given "negative" scenario can be quantitatively determined by combining its probability of occurrence (typical or proper of the given scenario) and the magnitude/severity/extent of the related consequences (*e.g.*, damage and/or loss that can be computed considering the expected number of fatalities in a given period of time or per unit of exposure time, the subject exposition, the expected damage, the vulnerability of the subject that is exposed to a given hazard, and the expected disutility). Other risk-related concepts are [12]: 1) Subjectivity (*e.g.*, decision maker or user, person or society, *etc.*); 2) Time (*e.g.*, risk related to today or yesterday, based on different boundary conditions); 3) Space (*e.g.*, risk referred to here or there); 4) Uncertainty. Fig. (**3a**) illustrates nine examples of risks that refer to **critical road infrastructures (CRI)**, including attacks (homeland security, left, 2a1: highway attack, 2a4: cyberattack; 2a7: bomb attack), natural disasters (centre, 2a2: earthquake; 2a5: flooding; 2a8: landslide), obsolescence- and decay-related failures (right, 2a3: pavement failure; 2a6: friction decay; 2a9: bridge failure). Fig. (**3b**) focuses on the relationship between asset management, (homeland) security, and safety, where asset management (including pavement management) mostly impacts safety (freedom from risk or harm as a result of unintentional acts) but could also affect security (freedom from risk or harm resulting from violence or other intentional acts). It seems relevant to highlight that land transport systems may be affected by different types of risks, pertaining to different components (Fig. **3b**). The concept of road safety necessarily includes the consideration of users and infrastructures (probability of accident, P_A). In contrast, the concept of security may address, for example, the structural integrity of embankments, tunnels and bridges, P_{ST}, (infrastructure), or data integrity attacks in autonomous vehicle networks [13, 14].

Risk matrices [12] can be used to represent the relation between probabilities (columns of the matrix) and consequences (rows of the matrix), which grow from left to right, and from the bottom to the top, respectively.

Berdica [12] analysed road transportation system **vulnerability** from both a safety and a level of service sufficiency point of view, and partially reviewed the concept of reliability. Vulnerability can be defined [12, 15] as a susceptibility to accidents that reduce road network accessibility of the whole road system (*i.e.*, not only of the physical network).

Outaly [16] demonstrated the efficacy of V2V and V2I communications towards reducing the risk of collision (as well as reducing CO_2 emissions). Similarly, Sepulcre and Gozalvez [17] presented V2V applications for traffic safety. These studies highlight that ICT is a tool to increase safety and reduce the probability of accidents. Liu and Fan [18] demonstrated the effectiveness of strain data in terms of impact on failure probability analyses of concrete bridge girders.

Frangopol [19] focused on the relationship between reliability and structural monitoring data. These studies point out that monitoring data provide information that reduces the probability of structural failure.

Finally, Troisi and Castaldo [20], outlined a theoretical framework for the risk management of road infrastructures from the perspective of organizational studies and engineering science. In more detail, they focused on the potential of satellite data obtained from differential interferometric synthetic aperture radar in a geographical information system platform.

In turn, **accessibility** [12] represents the opportunity (offered by the system mentioned above) to reach a given location and can be increased acting on the number of routes, or on the number of services reachable on a given route or within a certain time budget. Furthermore, accessibility [12] can be seen from both the demand and the supply sides, and the choice of point of view is important for the quantification of the consequences (*e.g.*, delay). In particular, the first point of view (demand side) relates to the goodness of functioning of a given route, while the second one (supply side) deals with the existence of a functioning route that makes the journey worthwhile (*i.e.*, a route/link/road that connects two locations in a given period of time, and at a given cost; a concept that is known as **serviceability**). Hence, the aforementioned consequences can be properly calculated if the second point of view is used. **Negative scenarios/events** [12] that affect the road transportation system's vulnerability and serviceability include extremely adverse weather, the occurrence of physical failures (loss of structural **integrity**), traffic accidents, and intentional harm (*e.g.*, wars or terroristic actions). Note that the vulnerability is connected to the consequences of negative scenarios/events, regardless of the probability of occurrence of that negative occurrence [12]. Another important concept is **robustness** [12]. It can be associated with the "ability of a system to withstand strain", and is the opposite of vulnerability. At the same time, the concept of **resilience** [12, 21, 22] is often associated with the aforementioned systems and refers to the ability (in terms of speed and degree of recovery) of a system to "return to normal", or "reach a new state of equilibrium", or "restore the original serviceability level" after the occurrence of an event/perturbation. Usually, congestion is the main parameter used to address traffic issues [23]. With the growing increment of user mobility, the importance of **reliability** is substantially growing [12, 23]. Importantly, reliability can be seen as a sort of complement of vulnerability, *i.e*. "*vulnerability in road transportation system is reliability, meaning adequate serviceability under the operating conditions encountered during a given period* " [12]. Reliability is linked to the concepts of (1) connectivity with the given destination (terminal reliability), (2) time (reliability of travel time), (3) probability to handle a given amount of traffic (capacity reliability), and (4) traffic flow (considering normal conditions, and recurrent and non-recurrent network congestions). It is possible to state that a road network is "reliable" [12] if the traffic service provided by the network, even in case of route interruption due to the occurrence of negative scenarios (*e.g*., accident, maintenance, natural disaster, *etc*.), is able to offer alternative routes to the users. There are several policy instruments to manage transportation networks' reliability [23], physical expansion of capacity, better management of capacity, pricing mechanisms to deliver a market for reliability, and use of information systems to mitigate unreliability. Despite this, reliability is rarely used as a parameter in cost-benefit assessments carried out during transport policymaking. Consequently, reliability targets and indicators should be selected with caution and taking into account both network operator and user perspectives [23].

Reliability, availability, maintainability, and safety (**RAMS**) analyses can be used to assess the performance of a system with respect to pre-defined requirements. RAMS analyses can be used for transportation systems [33, 34], although this approach is not comprehensive because of the fact it is not balanced from an economic point of view. Life Cycle Costing analysis can be used to fill this gap [34, 35]. The relationships among the diverse risk-related concepts analysed above are summarised in Fig. (**4**).

Table **1** and Fig. (**5**) illustrate the overall framework, *i.e*., the conceptual scheme to describe road risks taking into account both traditional and innovative methods and strategies.

2.3. Causes and Remedies for the Dominant Risks: Discussion

By referring to critical road infrastructures, **Traffic** affects environmental and operational impacts, safety and efficiency of transportation systems, and can be analysed (under normal or congested conditions) using data from measurements and/or models. Importantly, traffic models should be always properly validated, and, to this end, micro-simulation models can be effectively used (especially during the calibration process [47]).

The risks of **accidents** can increase because of extrinsic factors (*e.g*., driving behaviour, driving dynamics, environment, vehicle speeds) and/or intrinsic factors (*e.g*., **road geometry inconsistency**) [37 - 39]. In particular, intrinsic parameters, such as horizontal radius, section length, and longitudinal slope, can be used to explain the entire safety process. For example, the horizontal radius affects road accidents' stochastic process, such as the section length. "**Speed inconsistency**" can be related to friction requirements (*e.g*., side friction coefficients). In such cases, road agencies have to make a consistent reduction of the speed limit [39]. To this purpose, a methodology for friction-based assessment of speed limits (based on braking distance and stability in curves in both wet and dry conditions) can be used [39]. Rasmussen [36] focused on the correlation between accident-related risk and the performance of decision-makers at different levels (*i.e*., from national to local government, policy and budgeting to company planning). He found that "*accidents are created by the interaction of potential side effects of the performance of several decision makers during their normal work*".

Table 1. Conceptual scheme of the study.

Transportation Infrastructures Main Elements	Structure (pavement, embankment, bridge approach, erosion, bridge, joints, tunnels, retaining walls, culverts); Safety barriers; Sensing system; Signs; Road markings; Road lighting; Other systems.
Risk-related Concepts	Risk [11, 12]; Probability [11, 12]; Magnitude [11]; Reliability [12, 23]; Robustness [12]; Resilience [12, 21]; Vulnerability [12]; Event [12]; Integrity [12]; RAMS [33, 34].
Causes of Increased Risk	• Decision-maker performances [36]; • Design and structural integrity-related: Speed and road geometry inconsistency [37 - 39]; Decay of pavement bulk and functional characteristic [39 - 42]; Safety barrier issues [43, 44]; Bridge approach settlement [45] and bridge collapse [46]. • Safety-related: Traffic [47]; Incident [12]; Accident [37]; Road signs issues [48]. • Environment- and health-related: Environment [49]; Hazmat spillage [42, 50]; Roadside hazards [51]; Earthquakes [52]; Floods [53]; Soil erosion of cut, fill, and cut-and-fill road sections [54]; Particulate matter resuspension [55]; • Unsatisfactory effectiveness and durability of smart IoT, and sensor-based solutions for maintenance and rehabilitation (*e.g*., applicators, strain gauges, cameras, communication protocols and systems, and different types of I2X communication systems).
Transport-related Performance, Characteristics, and Parameters	Accessibility [12]; Serviceability [12]; Degradable transport system [12]; Capacity [12]; Level of service [12]; Delays; Surface characteristics (*e.g*., friction, distress, drainability, and texture) [56 - 58]; Moduli [59]; Pavement Condition Index (PCI); Present Serviceability Index (PSI); International Roughness Index (IRI); Bridge-related ones; Tunnel-related ones; Level of soil erosion of cut, fill, and cut-and-fill road sections; Noise indicators [60 - 62]; Pollution indicators [63]; Other LCA (Life Cycle Assessment)-related indicators (*e.g*., carbon footprint) [50, 64]; Expected life; Hazmat; Debris.
Risk Mitigation Strategies	Improvement of network configuration and design [49]; Monitoring [65 - 68]; Evaluation QA/QC (Quality Assurance/Quality Control) [69 - 71]; Inspections and audits [72]; Maintenance [73]; Rehabilitation [74]; ICT; Cybersecurity; Asset management, AM [75].

Unsatisfactory levels of **friction and texture** or the decay of friction increase the risk of accidents. Friction is not the only property that can decay over time. In fact, especially for porous asphalts, **bulk and functional characteristic** undergo a reduction during the pavement's expected life, affecting performance, safety, and budget [39 - 41]. In particular [42], with a dry surface, road safety mainly depends on micro-texture (which, in turn, is strongly affected by petrology) and on macro-texture (related to aggregate gradation, mix volumetrics and construction procedures), while with a wet surface, and at high speeds, safety mainly depends on macro-texture and air voids that rule characteristics such as friction and chemical resistance.

Potholes, bottom-up cracking, top-down cracking, and other surface distress impact pavement integrity, accident risk, tyre disruption, and vehicle costs. Mitigation measures include monitoring and maintenance [75 - 80].

To this end, it is noted that the same maintenance and rehabilitation processes involve risks because of work zones (which affect road safety and user costs) and because of virgin materials (which affect environmental risks). The mitigation of these risks can be carried out through the improvement of pavement design and the improvement of maintenance and rehabilitation using **selective induction heating**. This latter consists in using electromagnetic radiations to selectively heat a doped target layer [73], taking advantage of the self-healing of asphaltic materials [81].

Another source of risk is the excess of **noise and loudness**, with consequences in terms of human health and Disability-adjusted life years (DALYs [82],). To this end, strategies to reduce these risks include low-noise pavements and noise barriers.

Risks can increase because of natural and anthropic causes. On the one hand, the action of the atmospheric agents and the climatic changes (**environment**) must be considered during the design and maintenance process of transportation infrastructures [49]. On the other hand, ordinary and hazmat transport can affect performance and properties (*e.g*., pavement wear, and chemical resistance to **hazmat spillage** [42, 50];). Note that **roadside hazards** can be added to the causes described above since they can be both natural and anthropic. Examples of roadside hazards are [51]: i) Materials fallen from vehicles and abandoned/damaged vehicles; ii) Dead animals, stray livestock, and intruding shrubs or grasses; iii) Accumulation of objects and materials (ponding of water, trees, oil spills) on the traffic lane sides; iv) Damaged /missing drainage lids, surrounds and grates; v) Missing, illegible/damaged safety signs, safety barriers, guard rails and fencing at critical locations.

Furthermore, roadway assets and networks are vulnerable also to dangerous events such as **earthquakes and floods**. Different methodologies (*e.g*., physical damage assessment methods that are based on fragility functions and vulnerability indexes, traffic disruption assessment methods that use accessibility and link importance indexes) can be used to assess the **seismic vulnerability** of road assets and networks [52]. Because of climate change, **flood** risk is increasing [53]. Usually, historical data about atmospheric events are used to estimate flood risk, and this approach may lead to errors. Simulations (based on damage pattern, flood characteristics, precipitation depth, duration, number of cycles and pavement structure designs) and impact factor analysis can be used to try to reduce the aforementioned errors [53]. Results showed that (i) short-duration exposure to extreme precipitation should not cause significant damage, (ii) extreme events may affect the International Roughness Index (IRI) of a pavement; (iii) the pavement damage ratio can increase if the number of event cycles increases, (iv) long duration and higher cycle extreme events can effectively reduce the road pavement expected life, and (v) the Mechanistic-Empirical Pavement Design Guide (MEPDG) should be improved to take into account natural hazards and moisture damage of saturated old and new hot mix asphalt (HMA).

Another source of risk is **soil erosion in cut, fill, and cut-and-fill road sections**, especially in under resourced-countries. Seutloali and Beckedahl [54] considered this source of risk as critical for comprehensive land management decisions and monitoring strategies and underlined the need for further applications of assessment methods and control measures. In the latter study, it was highlighted how road construction mainly affects hydrologic and geomorphic processes because of the fact that it acts on (1) hill-slope profile (modification of natural profile, and formation of steep slopes, which are susceptible to severe erosion), and (2) vegetation cover (removal). In particular, road cut and fill embankments with steep slopes that are covered with insufficient vegetation, the interception of subsurface flows, and the concentration of runoff from the road surface can dramatically alter the natural equilibrium. Erosion control measures (*e.g*., field measurements, soil erosion control techniques, or soil erosion prediction models) can be used to mitigate this risk. For example, soil erosion control techniques that promote revegetation have the potential to reduce runoff (both velocity and quantity) and soil loss. Unfortunately, (i) there is a lack of methods that are efficient (from a cost point of view) and versatile (*i.e*., operational across landscapes that are different in type and size), and (ii) although sophisticated monitoring techniques are available (*e.g*., remote sensing technologies for erosion mapping), resource scarcity for assessing large areas limits their applicability.

Road-related risks are strictly connected to **safety barrier issues** ([43, 44], Road barriers: DM 223/92 and subsequent documents [83], Road barriers: EN 1317, parts 1-4 [84 - 87]).

Grzebieta [43] focused on the most dangerous crashes: (1) side impacts into narrow objects (@ impact speeds greater than 40 km/h); (2) head-on and large engagement offset crashes (@ about 120 km/h); and (3) roll-over crashes. If rollover does not occur, properly designed roadside or median barriers (rigid, semi-rigid, flexible, or temporary) can be used to safely redirect the vehicle, so that airbag and seat belt pre-tensioning systems do not activate. Butāns [44] pointed out that proper criteria should be used for the selection of a safety barrier. Based on standards and results from crash tests and simulations [43, 44], it is possible to state that both vehicle and barrier must be designed considering crashworthiness characteristics, such as (1) the ability to quickly (over a short distance) redirect and/or decelerate a vehicle respecting human tolerance/comfort levels (avoiding vehicle roll-over); (2) the barrier "containment level" (Low angle containment, Normal containment, Higher containment, Very high containment [88]); (3) the barrier's "impact severity level", expressed using the Acceleration Severity Index (ASI) and the Theoretical Head Impact Velocity (THIV) index, and classified into three levels (from A=high safety to B and C= significant passenger injury [88]); (4) the barrier "deformations" expressed by the working width (*i.e*., the movement sideways of the barrier after the vehicle impacts, which usually ranges from zero to few centimetres for rigid barriers, and from zero to 1-2 meters for the flexible ones. The European Standard EN 1317 [88] defines the levels from W1 to W8, where W1≤0.6 m, and W8≤3.5 m, the dynamic deflection (D), and the vehicle overhang (O); and (5) the timing of the vehicle airbag triggering (late or unnecessary airbag activation must be avoided).

Road markings and signs affect road safety and accident risk [89, 90]. Quality control and maintenance can reduce the risks deriving from the decay of their characteristics over time.

Note that, apart from road materials [91], the **geometric design** of a road affects road safety and accident ratios [38] in both rural and urban contexts. Unfortunately, these factors are difficult to change unless rehabilitation is carried out. Importantly, road safety audits and road safety audit reviews are tools that allow associating a score to a road [92]. This is an important point to consider when setting up a model for risk assessment.

Bridge approach settlement is considered by Helwany [45] as the cause of unsafe driving conditions, rider discomfort, poor public perception of the state infrastructure, structural failure of bridges, and long-term maintenance costs. Bridge approach settlements mainly depend on the poor performance of pavement, bridge abutment, consolidation of the backfill materials, consolidation of the foundation's soils, and poor drainage. Possible mitigation methods are: (1) specifying more stringent backfill materials (granular foundation soils should be used instead of cohesive foundation soils [93],); (2) specifying compaction requirements (erosion and/or movement of backfill material can be avoided acting on embankment side slopes); (3) providing proper drainage; (4) use geosynthetic reinforced fill; and (5) use flowable fill controlled low strength material (which can be more expensive than geosynthetic reinforced fill for small quantity jobs).

At the same time, bump repair techniques include (i) asphalt patching or overlays, (ii) slab jacking for Portland cement concrete pavements, and (iii) replacement of the approach slab. In addition, it is recommended (1) to carry out inspections within six months of bridge completion, and (2) to use inclinometers to measure the lateral and vertical deflection of the backfill and foundation soils over time, as well as of embankment slopes and the related toes.

A further cause of road risk increase is related to **bridge collapses**. Deng [46] grouped the common factors resulting in a bridge collapse into two main categories: (1) Natural factors (*e.g*., flood, scour, earthquake, landslide, debris flow, hurricane, typhoon, and wind) and (2) Human factors (*e.g*., imperfect design and construction method, collision, vehicle overloading, fire, terrorist attack, lack of inspection and maintenance, *etc*.). In the same study cited above, collapse modes (for beam bridges, masonry arch bridges, steel arch bridges, and steel truss bridges) are reviewed and some mitigation measures are discussed. In more detail: (i) beam bridges need a proper design to avoid problems such as misalignment and failures; (ii) masonry and steel arch bridges should be designed to balance the in-plane and out-of-plane rigidities; (iii) steel truss bridges should have high levels of redundancy, and regular inspection and maintenance are needed to ensure high safety and serviceability levels; and (iv) flexible long-span bridges should be designed paying special attention on static stability, aerostatic stability (*i.e*., torsional divergence and lateral-torsional buckling), aerodynamic stability (*i.e*., flutter, buffeting, and vortex-induced vibration), stiffness and profile. If the aerostatic and the aerodynamic stabilities are not satisfied, considerable displacements or stresses can occur. To avoid wind-induced problems, the optimization of stiffness and profile is needed. Bridge-related risks are (1) Scour, caused by fast-flowing water (more attention should be paid to the scour depth prediction because of the fact that the available empirical equations, models, and technologies lack accuracy; real-time monitoring systems are needed [94]); (2) Bridge collisions (investigations on the bridge response to vehicles/ vessels collisions are needed); (3) Overloading (new intelligent systems can be useful to define loading-carrying capacity and restrict vehicle weight); (4) Wave loads during natural disasters (especially for coastal bridges during hurricanes and/or for bridges during earthquakes, where methods and formulas are able to estimate wave-structure interaction and to predict wave loads on bridge components are needed); (5) harmful vibrations caused by wind. Indeed, fluid-structure interactions are complex and additional effort is needed on (i) the application of new light materials, (ii) the extension of bridge span length, and (iii) the definition of the most important parameters for wind-resistant design. Finally, for the stability of arch masonry bridges, further studies on dilatancy accompanying sliding between adjacent blocks are needed.

The structural integrity of bridges, embankments and pavements is critical also from another standpoint. Indeed, it is strictly related to **homeland security** and the **dual use** of infrastructures [95]. Indeed, under the EU Regulation above, road surfaces should have the capacity to withstand "movements or transport of the overweight military assets on an occasional basis" (road/bridge gross weights of 130 t). **Bridge joints** are another source of risk for transportation infrastructures because they may undergo different types of failure [96]. Strategies to mitigate the associated risks include design and maintenance.

Many sources of risks relate to **tunnels** [97], including structural and functional problems, failure of lighting, fire-related risks [98], issues related to air filtration plants, and terroristattacks.

Road lighting is another source of risk and mitigation (cf. Road lighting: EN 13201, parts 1-5 [99]. Road lighting: EN

12665 [100]. Road lighting: Interegcentral Europe Dynamic Light (Interreg Central Europe)).

Events such as earthquakes, floods, traffic accidents, adverse weather, and human actions (*e.g*., poor maintenance interventions or industrial activities) affect the level of degradation of the transportation systems, and, for this reason, the term **Degradable Transportation Systems** (DTS) [12] was suggested. Based on this concept, an integrated equilibrium model, to estimate network reliability as a function of elastic traffic demand, independent component states (*e.g*., road capacity), and different levels of degradation, was proposed [12]. Note that, usually [12]: 1) Traffic demand is modelled as a constant variable; 2) Levels of degradation are assumed to vary between "full capacity" and "zero capacity". 3) The aforementioned model considers the socio-economic impact of the levels of degradation of a system's component, which grows when the time for repair/replacement increases [101].

Note that the degradability above pertains also to the **obsolescence** of the infrastructure and its ICT parts [102]. Traffic flow is crucial for both safety and security. It should be noted that to solve the traffic equilibrium problem, the following concepts should be considered. The degradation affects the **capacity** of the network (capacity degradation) and, consequently, its reliability, even though each network has a "reserve capacity" that should contain the fluctuation of the travel demand [12]. Consequently, the probability that a given traffic demand can be put up (at a sufficient **level of service**) by a network is defined as "capacity reliability" [12]. The combination of capacity reliability and travel time could be used as a comprehensive performance measure of the road network [12]. Other sources of risks refer to the use of electronics and telecommunication in smart and current roads [84 - 86].

For the use of optical fibres in transportation infrastructures and smart city applications, note that, apart from their use as a medium for telecommunication and computer networking, they can be used as sensors because of the dependency of several requested parameters (*e.g*., strains, temperatures, pressures) on the characteristics of the transmitted signals (*e.g*., intensity, phase, polarization, wavelength, and transit time). Consequently, they may be used also for safety-related purposes (*e.g*., accident detection and inappropriate position/speed of cars and pedestrians), traffic engineering purposes (*e.g*., speeds, congestions, times, vehicle count), and infrastructure-related issues (*e.g*., rockfall, landslide, and falling trees). Consequently, their failures (*e.g*., facet oxidation, contact degradation, and crystal grown-in defect) can involve massive risks for transportation systems and infrastructures (*e.g*., increased accident ratio, loss of information about the structural health status, loss of information about the load distributions). When it comes to setting up specific mitigation strategies, it is noted that these tasks are crucial but are very complex [103]. Furthermore, they involve many interacting technologies and fields (*e.g*., optical fibres, materials, structures, and transportation [104],).

For the use of radio frequency identification, **RFID** [105], note that RFID-based systems may consist of a laptop, a reader, an antenna, and an RFID, where the connections between the elements above are cabled with the exception of the last one (antenna to RFID tag). In turn, the RFID consists of a microchip and an integrated antenna. They can provide information about materials transportation, transportation security, and cracks [106]. At the same time, failures in crack monitoring could imply delays in pavement management. This type of risk appears quite high because the reliability of RFID tags is impaired by the same stresses that asphalt concretes undergo. To this end, increasing the number of tags and the frequency of readings can minimise this class of risk.

For **strain gauges** (electric or optical), they measure strains and their malfunctioning may affect monitoring, maintenance, and rehabilitation, with consequences in terms of risk of accidents. Here, possible strategies to reduce the risks include an increase in the number of sensors and the improvement of the supply chain (sensor, data log, energy supply, telecommunication). This applies also to Brillouin distributed fibre sensors, where continuous, real-time measurements along the entire length of a fibre optic cable are carried out [107].

This applies also to **load cells**, **weight-in-motion** devices, and **piezoelectric** devices, used to control how loads are distributed along the carriageway. Their use is important to assess the traffic spectrum in the pursuit of infrastructure management and security controls.

Importantly, **accelerometers and microphones**, used in monitoring infrastructure response (*e.g*., resonant frequencies), may suffer malfunctioning or failures and this impacts the promptness of maintenance and other strategies (*e.g*., road or bridge closure).

Other components that impact risk and reliability are **cameras and traffic lights**, with consequences on traffic management and infrastructure security and management.

When it comes to **data transmission**, network failures may impact risks in terms of accidents and infrastructure monitoring.

Air quality monitoring, especially in the urban context, is becoming more and more important, where, for example, the particles generated in the pavement-tyre interface are re-suspended and impact bystanders' health (*e.g*., risk of respiratory infections). Sensors can detect Carbon dioxide (CO_2), Carbon monoxide (CO), NO, Nitrogen Dioxide (NO_2), and particulate matter (PM). These indicators help understand the quality of air. For example, PM concentrations are affected by pavement-tyre interaction (turbulence and resuspension) and impact human health. Failure in detecting and monitoring these indicators can increase the risk of inappropriate response to high PM levels, where pavement- and traffic-related mitigation strategies are supposed to be implemented [108]. Importantly, chemical detection is of paramount importance also by referring to threats (terrorism, weapons of mass destruction). Toxic chemical substances can be detected through wireless sensors and sensor networks [109].

Similarly, **road weather information systems** (RWIS) consist of 1) several environmental sensor stations (ESS), each one including sensors (*e.g*., thermometers, vanes, anemometers, udometers, air humidity sensors, pavement and subsurface temperature sensors, sensors for assessing pavement dry/wet/frozen state, sensors for assessing the amount of deicing chemical on the roadway and the freezing point of the road service, cameras), and remote processing units, RPUs. 2) Central processing units, CPUs. Indeed, RPUs have limited processing power and the data are sent from RPUs to the CPU. This latter is usually located close to a highway maintenance facility. CPU includes a database and other applications to collect, disseminate, and archive RWIS data [110]. 3) user interfaces (connected to the CPU). 4) other sources of information, including forecasts. Many opportunities, challenges and risks relate to RWISs, because of their ability to predict (weather and conditions) and consequently help manage (*e.g.*, traffic, maintenance, work zones, and rehabilitation processes), inherent risks refer to wrong predictions due to unsatisfactory data processing or/and biased data. By referring to cameras, it is noted that their use can support road maintenance, crisis management, and homeland security (criminal law enforcement).

Note that **poles** (or smart poles) are part of smart cities/roads and can provide WiFi hotspots for different distances, smart lights, weather stations, cameras, and EV charging stations. The risks associated are the ones discussed above for each corresponding item.

Electrified roads (either overhead wiring or road-embedded power lines) are currently quite costly but they could allow electrified transport among most adjacent major cities [111]. Their interaction with pavement structure poses opportunities and challenges [112] but risks are quite high in terms of decay of the overall structural health status of the pavement (durability) and proper technologies to maintain, preserve, and rehabilitate are needed. Electrified roads are an emerging technology and standardizations and regulations are still missing. Consequently, matters such as security should be properly addressed [113].

On-board sensors (or in-vehicle sensors) are not included in transportation structures but they affect the overall performance of a transport system. They refer also to onboard diagnostics, Anti-lock Braking Systems, emissions monitoring, pavement monitoring (accelerometers, in-tyre sensors [114], support to automated driving, short- (ultrasonic, infrared, and capacitive sensors) and long-range (scanners and computer vision technologies) sensors for the representation of vehicle surroundings [115]. To this end, note that the knowledge of vehicle surroundings can come from different sources, such as onboard sensors (as mentioned above), sensors in the infrastructure, and communications (V2X, I2X). Failures of the systems above affect road safety. Mitigation measures are quite difficult to set up but the same V2V communication systems could help improve the single-vehicle representation of vehicle surroundings.

In the new context of the massive use of sensors for multiple purposes, the reliability of transportation infrastructures could depend on the reliability of these systems and namely on the **failure probability of computing and communication processes** (*e.g.*, infrastructure to everything, I2X, vehicle to everything, V2X, and pedestrian to everything, P2X, communications [116, 117]. This issue affects infrastructure integrity, risk, resilience, autonomous vehicles, road safety, and the same use of transportation infrastructures as lifeline infrastructure where the failure of these lifeline services during natural hazard events could impact populations by exacerbating the hazard itself and/or hindering their ability to respond to or recover from the event [118].

3. MODELLING

Based on the analyses carried out above, in this section, the relationship between infrastructure-related risks and factors is modelled and three new equations are set up (equations 1-3). The risk (R) associated with a given functional unit (FU) at a given time t can be related to the corresponding reliability, RE, and structural integrity, SI, through the following equation:

$$R(FU,t) = 1 - RE(FU,t) = P(FU,t) \cdot M(FU,t) = F(SI) \quad \textbf{(1)}$$

Where R is the risk, which is a function of congestion, failure, accident, environmental and health impact, FU stands for the functional unit, t for time, RE is the reliability, P is the probability, M is the magnitude, SI is the structural integrity, and F stands for function.

By referring to (Fig. **5**):

- The following factors affect P: 2-8, 11, 12, 16, 18, 19, 21-23, 26-29 [92].
- The following factors affect M: 1, 2, 5-10, 13-15, 17, 21.
- The following factors affect structural integrity: 2, 13-15, 21, 24, 25, 34.
- The following factors pertain to R: 30-33.

The reliability of a transportation infrastructure depends on its ability to allow traffic to flow without accidents. This includes the consideration of the following aspects:

- The level of safety of the road [92];
- Traffic spectrum (flows and types of vehicles);
- The availability of information to users (*e.g.*, drivers);
- The redundancy of the network [119];
- The ability to serve after a major hazard.

Both the concept of structural integrity and reliability may refer to many risks, including accidents, P_A, and integrity-related P_{ST}. For safety (P_A), the safety level can be assessed through the running total described [92]. This algorithm provides a number in (0,100).

This number expresses a probability (I, in percentage). Anyhow, this type of consideration must be linked to the actual use of the infrastructure with respect to its highest traffic potential (flow-to-capacity ratio Q/C). It is noted that if this ratio were null, the corresponding safety level would be without any consequences on P_A. On the other hand, having a transportation infrastructure with structural failures would hinder future traffic from benefiting from the infrastructure (security-related instances).

Finally, it could be supposed that redundancy or connectivity (existence of alternative infrastructures, *i.e.*, detours) and the existence of systems to communicate among users, infrastructure, and stakeholders (*e.g.*, I2X, V2X, and P2X) would offer future possibilities and further opportunities to users to withstand threats.

Based on the above, the following model is herein proposed for safety-related purposes (P_A):

$$P_A = \left(\frac{100-I}{100}\right) \cdot (1-inf)\frac{Q}{C} \quad \textbf{(2)}$$

For structural integrity, the probability of related failure, P_{ST}, depends on road sections and namely viaducts, tunnels, or earthworks, including their characteristics and length.

$$P_{ST} = \frac{(a_1 V_{\%} + a_2 T_{\%} + a_3 R*_{\%})}{a_1} \cdot \left[\varepsilon_1 \frac{Q}{C} + \varepsilon_2\right](1-inf) \quad \textbf{(3)}$$

where

- P_A and P_{ST} are probabilities, defined in 0,1.
- *inf* refers to a measure of information and communication elements. A network-level redundancy involves the use of network equipment and redundant links, including routers (to allow connecting devices) and switches (to allow a sender to multicast by a switch). *inf* varies from 0 (no information) to 1.
- Q stands for traffic flow and C for capacity. Consequently, Q/C basically ranges from 0 to 1.
- $V_{\%}$, $T_{\%}$ and $R*_{\%}$ are the lengths (in percentage) of viaducts, tunnels and remaining sections (earthwork). Each of them varies from 0 to 1, being their sum of 1.
- a_1, a_2, a_3 are the corresponding weights, where $a_1 > a_2 > a_3$.
- ε_1 and ε_2 are coefficients that take into account the fact that integrity-related risk could be different from 0 also in the case of zero-standing people on the road. It is $\varepsilon_1 + \varepsilon_2 = 1$.

$\varepsilon_2 > 0$ expresses the probability of structural failure for example due to a terrorist attack. It depends also on strategic considerations. Note that *I*, *inf*, *C*, and a_i are affected by obsolescence, attacks (*e.g.*, bomb and radiological dispersion device), as well as by dual-use (civil and defence use), natural disasters, and other emergencies.

Fig. (**6**) illustrates how the choice of ε_1 and ε_2 and the parameters *Q/C*, *I*, and *inf* affect the probability that refers to accidents, P_A, and the probability that refers to structural failure risk, P_{ST}.

LIMITATIONS OF THE STUDY AND CONCLUSIONS

In this study, a model was set up dealing with the safety and security of transportation infrastructures in the context of information and communication technologies. Both the objects and the perspectives are essentially prototypical and deserve further study. Apart from the model set up to consider the impact of information in terms of risk and probability management, further studies will be also needed to assess model uncertainty, in terms of the following two aspects:

- The aleatoric uncertainty. This refers to data randomness, that is, to the variability of data (statistical uncertainty)
- The epistemic uncertainty. This refers to uncertainty caused by a lack of knowledge (*i.e.*, systematic uncertainty).

Based on the above, the following conclusions can be drawn:

1) Transportation infrastructures are complex systems and their operation depends on many factors, including design, management, and ICT-related factors.

2) Additionally, these factors not only impact safety but also security. In the end, this poses issues and opportunities in terms of critical information infrastructure protection.

3) The reliability and integrity of transportation infrastructures are crucial factors for society's development and homeland security. Based on the above, a model was set up to express the probability of accident-related and structural health-related occurrences.

4) Studies demonstrate that:

- Asset management and homeland security are strictly interrelated and physical and soft infrastructures must be taken into account for resilience and reliability.
- The protection of critical information infrastructures affects not only ICT operations but also critical infrastructures (particularly transport infrastructures).
- The doctrine of asset management (including pavement management) needs the effort to evolve towards the inclusion of ICT-related items, their life cycle and their effectiveness in improving both the life cycle of physical items (*e.g.*, pavement and its ability to allow safe operations) and its resilience (behaviour after attacks and natural disaster). This extension of asset management theory could help homeland security through a bottom-up approach.

Even if a tentative analysis of the model was performed, more studies and experiments are needed to improve and validate the proposed equations.

LIST OF ABBREVIATIONS

CIIs	=	Critical information infrastructures
CIP	=	Critical infrastructure protection
DTS	=	Degradable Transportation Systems

CONSENT FOR PUBLICATION

Not applicable.

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CONFLICT OF INTEREST

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REFERENCES

[1] The Investopedia Team, "Infrastructure: Definition, meaning, and examples", Available at: https://www.investopedia.com/terms/i/infrastructure.asp

[2] "A framework for critical information infrastructure risk management", Available at: https://www.microsoft.com/en-us/cybersecurity/content-hub/framework-critical-information-infrastructure

[3] CISA, "Critical infrastructure sectors", Available at: Https://Www.Cisa.Gov/Critical-Infrastructure-Sectors

[4] M. di Prisco, "Critical infrastructures in Italy: state of the art, case studies, rational approaches to select the intervention priorities", *In: proceedings of fib symposium. concrete: innovations in materials, design and structures.,* 2019 pp. 27-29 Krakow, Poland

[5] D.L. Alderson, R.P. Darken, D.A. Eisenberg, and T.P. Seager, "Surprise is inevitable: How do we train and prepare to make our critical infrastructure more resilient?", *Int. J. Disaster. Risk. Reduct.,* vol. 72, p. 102800, 2022. [http://dx.doi.org/10.1016/j.ijdrr.2022.102800]

[6] Commission of the European Communities, *Communication from the commission on a european programme for critical infrastructure protection.* Brussels, .

[7] R. Fedele, F.G. Pratico, R. Carotenuto, and F. Giuseppe Della Corte, "Instrumented infrastructures for damage detection and management", *2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS).,* 2017 Naples, Italy. [http://dx.doi.org/10.1109/MTITS.2017.8005729]

[8] S. Park, W.S. Yi, and B.N. Noh, "The detailed evaluation criteria for designation of critical information infrastructure in the field of broadcasting and communication", *WSEAS. Trans. on Info. Sci. and Appl.,* vol. 7, no. 2, pp. 252-262, 2010.

[9] N. De Liso, and L. Zamparini, "Innovation, transport security and supply chains: A review", *Transp. Rev.,* vol. 42, no. 6, pp. 725-738, 2022. [http://dx.doi.org/10.1080/01441647.2022.2105415]

[10] E. Cascetta, *Transportation systems engineering: Theory and method.,* vol. 49. Kluwer accademic publisher., 2001. [http://dx.doi.org/10.1007/978-1-4757-6873-2]

[11] T. Aven, "Risk assessment and risk management: Review of recent advances on their foundation", *Eur. J. Oper. Res.,* vol. 253, no. 1, pp. 1-13, 2016. [http://dx.doi.org/10.1016/j.ejor.2015.12.023]

[12] K. Berdica, "An introduction to road vulnerability: What has been done, is done and should be done", *Transp. Policy,* vol. 9, no. 2, pp. 117-127, 2002. [http://dx.doi.org/10.1016/S0967-070X(02)00011-2]

[13] A. Ghosal, S.U. Sagong, S. Halder, K. Sahabandu, M. Conti, R. Poovendran, and L. Bushnell, "Truck platoon security: State-of-the-art and road ahead", *Comput. Netw.,* vol. 185, p. 107658, 2021. [http://dx.doi.org/10.1016/j.comnet.2020.107658]

[14] A. Anwar, T. Halabi, and M. Zulkernine, "A coalitional security game against data integrity attacks in autonomous vehicle networks", *Vehicular. Commun.,* vol. 37, p. 100517, 2022. [http://dx.doi.org/10.1016/j.vehcom.2022.100517]

[15] S.A. Hassan, H.A. Amlan, N.E. Alias, M.A. Ab-Kadir, and N.S.A. Sukor, "Vulnerability of road transportation networks under natural hazards: A bibliometric analysis and review", *Int. J. Disaster. Risk. Reduct.,* vol. 83, p. 103393, 2022. [http://dx.doi.org/10.1016/j.ijdrr.2022.103393]

[16] F. Outay, F. Kamoun, F. Kaisser, D. Alterri, and A. Yasar, "V2V and V2I communications for traffic safety and CO2 emission reduction: A performance evaluation", *Procedia. Comput. Sci.,* vol. 151, pp. 353-360, 2019. [http://dx.doi.org/10.1016/j.procs.2019.04.049]

[17] M. Sepulcre, and J. Gozalvez, "Experimental evaluation of cooperative active safety applications based on V2V communications", *VANET '12: Proceedings of the ninth ACM international workshop on Vehicular inter-networking, systems, and applications,* 2012pp. 13-20 New York, USA [http://dx.doi.org/10.1145/2307888.2307893]

[18] Y. Liu, and X. Fan, "Use of monitoring extreme strain data for failure probability analysis of concrete bridge girder: An optimal vine Gaussian-copula model", *Structures.,* vol. 44, pp. 274-283, 2022. [http://dx.doi.org/10.1016/j.istruc.2022.08.016]

[19] D.M. Frangopol, A. Strauss, and S. Kim, "Bridge Reliability Assessment Based on Monitoring", *J. Bridge. Eng.,* vol. 13, no. 3, pp. 258-270, 2008. [http://dx.doi.org/10.1061/(ASCE)1084-0702(2008)13:3(258)]

[20] R. Troisi, and P. Castaldo, "Technical and organizational challenges in the risk management of road infrastructures", *J. Risk. Res.,* vol. 25, no. 6, pp. 791-806, 2022. [http://dx.doi.org/10.1080/13669877.2022.2028884]

[21] C. Wan, Z. Yang, D. Zhang, X. Yan, and S. Fan, "Resilience in transportation systems: A systematic review and future directions", *Transp. Rev.,* vol. 38, no. 4, pp. 479-498, 2018. [http://dx.doi.org/10.1080/01441647.2017.1383532]

[22] A. Soltani-Sobh, K. Heaslip, and J. El Khoury, "Estimation of road network reliability on resiliency: An uncertain based model", *Int. J. Disaster. Risk. Reduct.,* vol. 14, pp. 536-544, 2015. [http://dx.doi.org/10.1016/j.ijdrr.2015.10.005]

[23] OECD - International Transport Forum, *Improving reliability on surface transport networks.,* OECD Publishing: Paris, 2010. [http://dx.doi.org/10.1787/9789282102428-en]

[24] CBS News, Available at: https://www.cbsnews.com/

[25] "WIKIPEDIA", Available at: https://www.wikipedia.org/

[26] AboutCivil, Available at: https://www.aboutcivil.org/

[27] "National Herald", Available at: https://www.nationalheraldindia.com/national/earthquake-of-35-magnitude-hits-katra-in-jk

[28] "PNGtree", Available at: https://es.pngtree.com/so/informatica

[29] "Thairath", Available at: https://www.thairath.co.th/news/auto/tips/2396006

[30] Public Domain Vectors, Available at: https://publicdomainvectors.org/it/vettoriali-gratuiti/Immagine-vettoriale-stradali-scivolose-traffico-simbolo/24082.html

[31] Available at: https://crosscut.com/2020/02/landslides-close-roads-washingtons-remote-towns-deal-isolation

[32] "WIRED", Available at: https://www.wired.it/attualita/politica/2019/08/14/ponte-morandi-un-anno-dopo/

[33] M. Graboń-Chałupczak, and M. Sitarz, "MATEC web conf", *12th International Road Safety Conference GAMBIT 2018 - "Road Innovations for Safety - The National and Regional Perspective.,* vol. 231, 2018 [http://dx.doi.org/10.1051/matecconf/201823104004]

[34] F.G. Praticò, and M. Giunta, "Proposal of a Key Performance Indicator for Railway Track Based on LCC and RAMS Analyses", *J. Constr. Eng. Manage.,* vol. 144, no. 2, p. 04017104, 2018. [http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0001422]

[35] D.P. Ashmore, and N.G. Harris, "Using risk analysis to determine the potential range of lifecycle costs for urban transit systems", *Transp. Rev.,* vol. 20, no. 4, pp. 403-420, 2000. [http://dx.doi.org/10.1080/014416400501506667]

[36] J. Rasmussen, "Risk management in a dynamic society: A modelling problem", *Saf. Sci.,* vol. 27, no. 2-3, pp. 183-213, 1997. [http://dx.doi.org/10.1016/S0925-7535(97)00052-0]

[37] F.G. Praticò, "Formulating a safety model and validating it by an experimental investigation on the A3 salerno-reggio calabria", Available From :https://www.siiv.net/site/sites/default/files/Documenti/firenze/firenze35.pdf

[38] R. Lamm, B. Psarianos, and T. Mailaender, "Highway Design and Traffic Safety Engineering Handbook",

[39] F.G. Pratico, *Speed limits and pavement friction: A theoretical and experimental study.,* vol. 12. *The Open Transp. J.*, 2018, pp. 139-149. [http://dx.doi.org/10.2174/1874447801812010139]

[40] F.G. Praticò, R. Vaiana, and S. Noto, "Photoluminescent Road Coatings for Open-Graded and Dense-Graded Asphalts: Theoretical and Experimental Investigation", *J. Mater. Civ. Eng.,* vol. 30, no. 8, p. 04018173, 2018. [http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0002361]

[41] F.G. Praticò, P.G. Briante, G. Colicchio, and R. Fedele, "An experimental method to design porous asphalts to account for surface requirements", *J. Traffic.Transp. Eng.,* vol. 8, Englishno. 3, pp. 439-452, 2020.

[http://dx.doi.org/10.1016/j.jtte.2019.05.006]

[42] F.G. Praticò, R. Vaiana, and M. Giunta, "Role Of Pavements Surface Properties In The Management Of The Road Safety For Ordinary And Hazmat Transport", *4th International Conference on Modern Technologies in Highway Engineering Poznan,* 2009 Poland

[43] R.H. Grzebieta, R. Zou, T. Jiang, and A. Carey, "Roadside hazard and barrier crashworthiness issues confronting vehicle and barrier manufactures and government regulatorsi", *Proc. 19th International Technical Conference on the Enhanced Safety of Vehicles,* 2005 Washington, USA

[44] Z. Butans, K.A. Gross, A. Gridnevs, and E. Karzubova, "Karzubova, Road safety barriers, the need and influence on road traffic accidents", *2nd International Conference on Innovative Materials, Structures and Technologies 30 September to 2 October 2015.,* 2015 Riga, Latvia [http://dx.doi.org/10.1088/1757-899X/96/1/012063]

[45] S. Helwany, T.E. Koutnik, and A. Ghorbanpoor, *Evaluation of Bridge Approach Settlement Mitigation Methods.,* Wisconsin Highway Research Program., 2007.

[46] L. Deng, W. Wang, and Y. Yu, "State-of-the-Art Review on the Causes and Mechanisms of Bridge Collapse", *J. Perform. Constr. Facil.,* vol. 30, no. 2, p. 04015005, 2016. [http://dx.doi.org/10.1061/(ASCE)CF.1943-5509.0000731]

[47] F.G. Praticò, R. Vaiana, and V. Gallelli, Transport and traffic management by micro simulation models: Operational use and performance of roundabouts.*WIT Transactions on the Built Environment.,* WIT Tran, 2012, pp. 383-394. [http://dx.doi.org/10.2495/UT120331]

[48] R. Saleh, and H. Fleyeh, Using supervised machine learning to predict the status of road signs.*Trans. Res. Procedia.,* vol. 62, pp. 221-228, 2022. [http://dx.doi.org/10.1016/j.trpro.2022.02.028]

[49] Y. Qiao, J. Santos, A.M.K. Stoner, and G. Flinstch, "Climate change impacts on asphalt road pavement construction and maintenance: An economic life cycle assessment of adaptation measures in the State of Virginia, United States", *J. Ind. Ecol.,* vol. 24, no. 2, pp. 342-355, 2020. [http://dx.doi.org/10.1111/jiec.12936]

[50] F.G. Praticò, R. Ammendola, and A. Moro, "Factors affecting the environmental impact of pavement wear", *Transp. Res. Part D Transp. Environ.,* vol. 15, no. 3, pp. 127-133, 2010. [http://dx.doi.org/10.1016/j.trd.2009.12.002]

[51] "Local Government & Municipal Knowledge Base - Australian government, Roadside hazards", Available at: http://www.lgam.info/roadside-hazards

[52] A.M. El-Maissi, S.A. Argyroudis, and F.M. Nazri, "Seismic vulnerability assessment methodologies for roadway assets and networks: A state-of-the-art review", *Sustainability.,* vol. 13, no. 1, p. 61, 2020. [http://dx.doi.org/10.3390/su13010061]

[53] D. Lu, S.L. Tighe, and W.C. Xie, "Impact of flood hazards on pavement performance", *Int. J. Pavement. Eng.,* vol. 21, no. 6, pp. 746-752, 2020. [http://dx.doi.org/10.1080/10298436.2018.1508844]

[54] K.E. Seutloali, and H. Reinhard Beckedahl, "A review of road–related soil erosion: An assessment of causes, evaluation techniques and available control measures", *Earth Sci. Res. J.,* vol. 19, no. 1, pp. 73-80, 2015. [http://dx.doi.org/10.15446/esrj.v19n1.43841]

[55] F.G. Praticò, and P.G. Briante, "Particulate matter from non-exhaust source", *11th International Conference "Environmental Engineering" (ENVIRO).,* 2020 Vilnius, Lithuania [http://dx.doi.org/10.3846/enviro.2020.622]

[56] F.G. Praticò, and A. Astolfi, "A new and simplified approach to assess the pavement surface micro- and macrotexture", *Constr. Build. Mater.,* vol. 148, pp. 476-483, 2017. [http://dx.doi.org/10.1016/j.conbuildmat.2017.05.050]

[57] F.G. Praticò, "Quality and timeliness in highway construction contracts: A new acceptance model based on both mechanical and surface performance of flexible pavements", *Construct. Manag. Econ.,* vol. 25, no. 3, pp. 305-313, 2007. [http://dx.doi.org/10.1080/01446190601042426]

[58] G. de León, L.G. Del Pizzo, L. Teti, A. Moro, F. Bianco, L. Fredianelli, and G. Licitra, "Evaluation of tyre/road noise and texture interaction on rubberised and conventional pavements using CPX and profiling measurements", *Road Mater. Pavement Des.,* vol. 21, no. sup1, pp. S91-S102, 2020. [http://dx.doi.org/10.1080/14680629.2020.1735493]

[59] S. Cafiso, A. Di Graziano, R. Fedele, V. Marchetta, and F. Praticò, "Sensor-based pavement diagnostic using acoustic signature for moduli estimation", *Int. J. Pavement Res. Technol.,* vol. 13, no. 6, pp. 573-580, 2020. [http://dx.doi.org/10.1007/s42947-020-6007-4]

[60] F.G. Praticò, and P.G. Briante, "Prediction of surface texture for better performance of friction courses", *Constr. Build. Mater.,* vol. 230, p. 116991, 2020. [http://dx.doi.org/10.1016/j.conbuildmat.2019.116991]

[61] F.G. Praticò, "Roads and Loudness: A More Comprehensive Approach", *Road Mater. Pavement Des.,* vol. 2, no. 4, pp. 359-377, 2001. [http://dx.doi.org/10.1080/14680629.2001.9689908]

[62] L. Teti, G. de León, L.G. Del Pizzo, A. Moro, F. Bianco, L. Fredianelli, and G. Licitra, "Modelling the acoustic performance of newly laid low-noise pavements", *Constr. Build. Mater.,* vol. 247, p. 118509, 2020. [http://dx.doi.org/10.1016/j.conbuildmat.2020.118509]

[63] S. Gulia, P. Goyal, S.K. Goyal, and R. Kumar, "Re-suspension of road dust: Contribution, assessment and control through dust suppressants—a review", *Int. J. Environ. Sci. Technol.,* vol. 16, no. 3, pp. 1717-1728, 2019. [http://dx.doi.org/10.1007/s13762-018-2001-7]

[64] T.M. Gulotta, M. Mistretta, and F.G. Praticò, "A life cycle scenario analysis of different pavement technologies for urban roads", *Sci. Total. Environ.,* vol. 673, pp. 585-593, 2019. [http://dx.doi.org/10.1016/j.scitotenv.2019.04.046] [PMID: 30999099]

[65] M. Merenda, R. Carotenuto, F.G. Della Corte, F.G. Pratico, and R. Fedele, "Self-powered wireless IoT nodes for emergency management", *20th IEEE Mediterranean Electrotechnical Conference, MELECON 2020,* 2020pp. 187-192 [http://dx.doi.org/10.1109/MELECON48756.2020.9140503]

[66] "Ministry of Infrastructure and Transport, Guidelines for risk classification and management, safety assessment and monitoring of existing bridges",

[67] F. Bianco, L. Fredianelli, F. Lo Castro, P. Gagliardi, F. Fidecaro, and G. Licitra, "Stabilization of a p-u Sensor Mounted on a Vehicle for Measuring the Acoustic Impedance of Road Surfaces", *Sensors (Basel),* vol. 20, no. 5, p. 1239, 2020. [http://dx.doi.org/10.3390/s20051239] [PMID: 32106391]

[68] B.P.Y. Loo, W.T. Hung, H.K. Lo, and S.C. Wong, "Road Safety Strategies: A Comparative Framework and Case Studies", *Transp. Rev.,* vol. 25, no. 5, pp. 613-639, 2005. [http://dx.doi.org/10.1080/01441640500115892]

[69] PIARC, "Evaluating the performance of automated pavement cracking measurement equipment", *Comité Technique 4.2 Interaction Route/Véhicule / Technical Committee 4.2 Road/Vehicle.,* vol. 28, 2012.

[70] F.G. Pratico, A. Moro, and R. Ammendola, "Modeling HMA bulk specific gravities: A theoretical and experimental investigation", *Int. J. Pavement Res. Technol.,* 2009. [http://dx.doi.org/10.6135/ijprt.org.tw/2009.2(3).115]

[71] F.G. Praticò, and R. Vaiana, "Improving infrastructure sustainability in suburban and urban areas: Is porous asphalt the right answer? And how?", *WIT Transactions on the Built Environment.,* vol. 128, 2012pp. 673-684 [http://dx.doi.org/10.2495/UT120571]

[72] F.G. Praticò, D. Catalfamo, and C. Lanciano, "Safety and reliability of a road: A prototypical study based on the directive 2008/96/EC", *4th Chinese-European Workshop on Functional Pavement Design, CEW,* 2016 Delft (NL) [http://dx.doi.org/10.1201/9781315643274-191]

[73] M.T. Bevacqua, T. Isernia, F.G. Praticò, and S. Zumbo, "A method for bottom-up cracks healing via selective and deep microwave heating", *Autom. Construct.,* vol. 121, p. 103426, 2021. [http://dx.doi.org/10.1016/j.autcon.2020.103426]

[74] S. Pearson, *Theory and technique of road construction.,* vol. 1-2. 2016.

[75] AASHTO, *Pavement Management Guide.,* 2nd ed 2012.

[76] T.F. Fwa, *The Handbook of Highway Engineering.,* CRC Press: Boca Raton, 2005. [http://dx.doi.org/10.1201/9781420039504]

[77] Y.H. Huang, *Pavement analysis and design.,* Pearson/Prentice Hall, 2004.

[78] M.L. Ralls, S.D. DeWitt, and R.B. Leahy, "Glossary of highway quality assurance terms fourth update", Washington DC., 2009.www.TRB.org

[79] J.L. Burati, R.M. Weed, C.S. Hughes, and H.S. Hill, *Optimal*

Procedures for Quality Assurance Specifications., Clemson, SC, 2016, pp. 29634-0911.
[80] F. Santagata, *Strade: Teoria e tecnica delle costruzioni stradali.,* vol. Vol. 1. Progettazione, 2016.
[81] B. Liang, F. Lan, K. Shi, G. Qian, Z. Liu, and J. Zheng, "Review on the self-healing of asphalt materials: Mechanism, affecting factors, assessments and improvements", *Constr. Build. Mater.,* vol. 266, p. 120453, 2021. [http://dx.doi.org/10.1016/j.conbuildmat.2020.120453]
[82] Z. Piao, K. Heutschi, R. Pieren, P. Mikhailenko, L.D. Poulikakos, and S. Hellweg, "Environmental trade-offs for using low-noise pavements: Life cycle assessment with noise considerations", *Sci. Total. Environ.,* vol. 842, p. 156846, 2022. [http://dx.doi.org/10.1016/j.scitotenv.2022.156846] [PMID: 35738370]
[83] Ministry of Public Works, "DM 223/92 - Regulation containing technical instructions for the design, approval and use of road safety barriers", Available From :https://www.gazzettaufficiale.it/eli/id/1992/03/16/092G0251/sg#:~:text=Gazzetta%20Ufficiale%20MINISTERO%20DEI%20LAVORI%20PUBBLICI%20DECRETO%2018,16-03-1992%29%20note%3A%20Entrata%20in%20vigore%20del%20decreto%3A%2031-3-1992
[84] "UNI EN 1317-1:2010, Road restraint systems - Part 1: Terminology and general criteria for test methods", Available From :https://standards.globalspec.com/std/1270984/EN%201317-1
[85] UNI UNI EN 1317, "Road restraint systems - Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers including vehicle parapets", Available From :https://infostore.saiglobal.com/preview/98698023876.pdf?sku=865361_SAIG_NSAI_NSAI_2058198
[86] UNI EN 1317-3:2010, "Road restraint systems - Part 3: Performance classes, impact test acceptance criteria and test methods for crash cushions", Available From :https://standards.globalspec.com/std/1272698/BS%20EN%201317-3
[87] UNI, UNI ENV 1317-4, "Road restraint systems: Performance classes, impact test acceptance criteria and test methods for terminals and transitions of safety barriers", Available From :https://infostore.saiglobal.com/en-us/Standards/UNI-ENV-1317-4-2003-1082953_SAIG_UNI_UNI_2522390/
[88] "UNI EN 1317, Road restraint systems",
[89] T. v. Dormidontova, and A. v. Filatova, "Research of Influence of Quality of Materials on a Road Marking of Highways", *Procedia. Eng.,* vol. 153, pp. 933-937, 2016. [http://dx.doi.org/10.1016/j.proeng.2016.08.256]
[90] T. Horberry, J. Anderson, and M.A. Regan, "The possible safety benefits of enhanced road markings: A driving simulator evaluation", *Transp. Res. Part F Traffic Psychol. Behav.,* vol. 9, no. 1, pp. 77-87, 2006. [http://dx.doi.org/10.1016/j.trf.2005.09.002]
[91] F.G. Praticò, and A. Moro, "In-lab and on-site measurements of hot mix asphalt density: Convergence and divergence hypotheses", *Constr. Build. Mater.,* vol. 25, no. 2, pp. 1065-1071, 2011. [http://dx.doi.org/10.1016/j.conbuildmat.2010.06.071]
[92] I. Wessels, and Steyn. W.J. VDM., Real-time monitoring of the extended road network by utilising telematics technology.*Funct. Pavement Design.,* CRC Press, 2016, pp. 1645-1656. [http://dx.doi.org/10.1201/9781315643274-181]
[93] AASHTO M 145-91, "Standard specification for classification of soils and soil-aggregate mixtures for highway construction purposes", Available From :https://global.ihs.com/doc_detail.cfm?document_name=AASHTO%20M%20145&item_s_key=00487409
[94] P. Merenda, Praticò, Fedele, Carotenuto, and Della Corte, "A Real-time decision platform for the management of structures and infrastructures", *Electronics.,* vol. 8, no. 10, p. 1180, 2019. [http://dx.doi.org/10.3390/electronics8101180]
[95] European Commission, *Commission implementing regulation.,* EU: Brussels, 2021, p. 1328.
[96] Z. Sun, and Y. Zhang, "Failure mechanism of expansion joints in a suspension bridge", *J. Bridge. Eng.,* vol. 21, no. 10, p. 05016005, 2016. [http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000942]
[97] S.P. Huang, and M.L. Guo, *Analysis and strategies of the common tunnel problems.,* Spriger Nature, 2015. [http://dx.doi.org/10.2991/aiie-15.2015.87]
[98] J. Gehandler, "Road tunnel fire safety and risk: A review", *Fire Sci. Rev.,* vol. 4, no. 1, p. 2, 2015. [http://dx.doi.org/10.1186/s40038-015-0006-6]
[99] EN, BS EN 13201, "Road lighting",
[100] CEN - EN 12665., "Light and lighting - Basic terms and criteria for specifying lighting requirements", Available From :https://standards.globalspec.com/std/10394098/EN%2012665
[101] Interreg Central Europe, "Dynamic light", Available at: https://www.interreg-central.eu/Content.Node/Dynamic-Light.html
[102] O. Dinu, "Reliability, safety and efficiency-challenges for transport infrastructures. international scientific journal", *TRANS. & MOTAUTO. WORLD.,* vol. 5, pp. 93-97, 2020.
[103] Y. Mitsunaga, Y. Katsuyama, H. Kobayashi, and Y. Ishida, "Failure prediction for long length optical fiber based on proof testing", *J. Appl. Phys.,* vol. 53, no. 7, pp. 4847-4853, 1982. [http://dx.doi.org/10.1063/1.331316]
[104] X. Chapeleau, J. Blanc, P. Hornych, J-L. Gautier, and J. Carroget, "Assessment of cracks detection in pavement by a distributed fiber optic sensing technology", *J. Civ. Struct,* vol. 7, no. 4, pp. 459-470, 2017. [http://dx.doi.org/10.1007/s13349-017-0236-5]
[105] E. Mustafa, *Radio frequency identification applications in pavement engineering.,* College Park ProQuest Dissertations Publishing: University of Maryland, 2010.
[106] F.G. Praticò, R. Fedele, V. Naumov, and T. Sauer, "Detection and monitoring of bottom-up cracks in road pavement using a machine-learning approach", *Algorithms,* vol. 13, no. 4, p. 81, 2020. [http://dx.doi.org/10.3390/a13040081]
[107] H. Wijaya, P. Rajeev, and E. Gad, "Distributed optical fibre sensor for infrastructure monitoring: Field applications", *Opt. Fiber. Technol.,* vol. 64, p. 102577, 2021. [http://dx.doi.org/10.1016/j.yofte.2021.102577]
[108] F. Amato, X. Querol, C. Johansson, C. Nagl, and A. Alastuey, "A review on the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods", *Sci. Total. Environ.,* vol. 408, no. 16, pp. 3070-3084, 2010. [http://dx.doi.org/10.1016/j.scitotenv.2010.04.025] [PMID: 20488509]
[109] R.A. Potyrailo, N. Nagraj, C. Surman, H. Boudries, H. Lai, J.M. Slocik, N. Kelley-Loughnane, and R.R. Naik, "Wireless sensors and sensor networks for homeland security applications", *Trends Analyt. Chem.,* vol. 40, pp. 133-145, 2012. [http://dx.doi.org/10.1016/j.trac.2012.07.013] [PMID: 23175590]
[110] "Road weather information systems (rwis) data integration guidelines", Available at: http://www.aurora-program.org
[111] S. Schwerdfeger, S. Bock, N. Boysen, and D. Briskorn, "Optimizing the electrification of roads with charge-while-drive technology", *Eur. J. Oper. Res.,* vol. 299, no. 3, pp. 1111-1127, 2022. [http://dx.doi.org/10.1016/j.ejor.2021.08.045]
[112] F. Chen, N. Taylor, and N. Kringos, "Electrification of roads: Opportunities and challenges", *Appl. Energy.,* vol. 150, pp. 109-119, 2015. [http://dx.doi.org/10.1016/j.apenergy.2015.03.067]
[113] M.G.H. Gustavsson, "Research & Innovation for Electric Roads", *35th International Electric Vehicle Symposium and Exhibition (EVS35) Oslo,* 2022 Norway
[114] L.G. Del Pizzo, F. Bianco, A. Moro, G. Schiaffino, and G. Licitra, "Relationship between tyre cavity noise and road surface characteristics on low-noise pavements", *Transp. Res. Part. D Transp. Environ.,* vol. 98, p. 102971, 2021. [http://dx.doi.org/10.1016/j.trd.2021.102971]
[115] F. Jiménez, "Road vehicles surroundings supervision: onboard sensors and communications", *Appl. Sci.,* vol. 8, no. 7, p. 1125, 2018. [http://dx.doi.org/10.3390/app8071125]
[116] K. Xiong, S. Leng, C. Huang, C. Yuen, and Y.L. Guan, "Intelligent task offloading for heterogeneous V2X Communications", *IEEE Trans. Intell. Transp. Syst.,* vol. 22, no. 4, pp. 2226-2238, 2021. [http://dx.doi.org/10.1109/TITS.2020.3015210]
[117] J.M. Lozano Domínguez, and T.J. Mateo Sanguino, "Review on V2X, I2X, and P2X communications and their applications: A comprehensive analysis over time", *Sensors.,* vol. 19, no. 12, p. 2756, 2019. [http://dx.doi.org/10.3390/s19122756] [PMID: 31248189]
[118] E.A. Singh, Compounding impacts of lifeline infrastructure failure during natural hazard events.*The Demography of Disasters.,* Springer International Publishing: Cham, 2021, pp. 189-210. [http://dx.doi.org/10.1007/978-3-030-49920-4_10]
[119] S. Vivek, and H. Conner, "Urban road network vulnerability and resilience to large-scale attacks", *Saf. Sci.,* vol. 147, p. 105575, 2022. [http://dx.doi.org/10.1016/j.ssci.2021.105575]