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3 KEY NOTIONS FOR ROAD TRANSPORT SUSTAINABILITY: RESILIENCE, CLIMATE ACTION AND ENERGY TRANSITION

Eric DIMNET, Senior adviser for Resilience, Energy and Climate, Mast Department, Gustave Eiffel University, Marne la Vallée, France, eric.dimnet@univ-eiffel.fr
Technical Advisor for Resilience and Climate Change, General Secretariat, PIARC, Grande Arche de la Défense, France, eric.dimnet@piarc.org
Chair of PIARC's Technical Committee "Environmental Sustainability in Road Infrastructure and Transport"

Abstract

In this paper, we study the relationship between resilience and sustainable development in order to determine the place of road resilience in the Sustainable Development Goals (SDGs) such as climate action and energy transition.

This study shows that road resilience is inseparable from adaptation to climate change, its mitigation and the energy transition. Therefore we address the issue of adapting road infrastructure to climate change and to the decarbonization of transport. It also emphasizes that resilience of road infrastructure is a necessary condition for any adaptation strategy and reminds us that the contribution of road transport to climate change mitigation overlaps in practice with the decarbonization goal resulting from energy transition.

Keywords: Sustainability, Road Transport, Resilience, Climateaction, Adaptation, Mitigation, Energy Transition

1. ORIGINS AND DEFINITIONS OF RESILIENCE

Up until the early 1970s, the only mention of resilience in the road world was to refer to the resilience modulus of material layers in pavement design. On the contrary, the notion of resilience has been the topic of numerous research studies that have led to multiple definitions of theoretical or applied scope in other domains. It has been studied in the fields of psychiatry, sociology, humanities and social sciences [1]. Moreover, the shift to humanities and social sciences has allowed the notion of resilience to evolve from a concept that defines or applies to a material or a person to a notion that characterizes a community or a society: we have thus moved from the resilience of individuals to that of territories or societies [2].

Resilience has thus become a polysemic term whose many definitions fall into two categories, depending on whether resilience is considered a property of a system or the process by which the system evolves following an internal or external disruptive solicitation referred to as impact or shock.

Resilience as a property (or as an intrinsic state).

Resilience is seen as an inherent quality of a system, an already present capacity that manifests itself at the moment of the impact. Seen this way, resilience is an innate or acquired quality, a potential that pre-exists the impact and that is revealed by it. One is less interested in the system's response than in its vulnerable elements or subsystems, which leads us to think ahead of a disruptive event and prepare to face it.

Resilience as a process.

Resilience is a dynamic process consisting of successive steps that follow the disrupted or damaged state of an impacted system to a stable state that may be its previous state or a different one called the restoration threshold. The state of the system is measured at each step by indicators that define its performance index and the duration of the recovery process is called the restoration time.

While resilience as a property provides a framework for prospective and preventive approaches to improve the resilience of a system, resilience as a process invites learning from past events and improving resilience to future impacts through feedback. The two definitions lead to relatively different methodological approaches on the theoretical level [3]. However, they are quite reconcilable for the road transport sector since, from a practical point of view, it is the intrinsic qualities of a system that determine the resilience process of a transport system when it undergoes a disruptive episode.

The use of the term resilience has become so popular that it now appears in numerous semantic fields such as risk management or adaptation to climate change and it is frequently confused with sustainable development; the confusion is accentuated by the fashion effect which consists of using the term resilience where sustainable development was used 20 years ago. Therefore, we must clarify the outlines, nature and limits of resilience in order to seek its logical connection with sustainable development [4].

However, even if the theoretical differences between resilience and sustainable development are real, to the point that some authors [5] suggest overcoming them by using the term resilient development, we could articulate them provided that we limit our investigations to a defined context such as transport or road transport. Therefore, we first look into sustainable development, its objectives and the place it gives to road transport, in order to find elements for characterizing and defining resilience and its connection with sustainability in the

context of road transport. The results of this study allow us to understand to what extent the resilience of road transport and infrastructure contributes to the sustainable development objectives of climate action and energy transition.

2. THE PLACE OF TRANSPORTATION IN SUSTAINABLE DEVELOPMENT GOALS (SDGS)

2.1. Sustainable development, 3 pillars for 17 objectives

What is sustainable development?

The best known definition of sustainable development comes from the Brundtland Report written by the UN World Commission on Environment and Development chaired by G. H. Brundtland and published in 1887 [6]:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs ".

The commission, whose mission was to examine the critical issues of environment and development, "focused on the areas of population, food security, loss of species and genetic resources, energy, industry, and human settlements - realizing that all of these are interrelated and cannot be treated in isolation from one another" [6]. It introduced and defined sustainable development, later popularized at Rio's Earth Summit in 1992.

Sustainable development is based on three pillars that represent the three dimensions of human activity that it has to reconcile: the environmental pillar, which often appears as the first issue of sustainable development, the social pillar, resulting from the observation of a growing social inequality and the economic pillar, which is naturally connected to the concept of development.

The Venn diagram of sustainable development established from these three pillars (fig. 1) enables the determination of objective and practical conditions development must meet to be sustainable: be liveable, fair and viable.

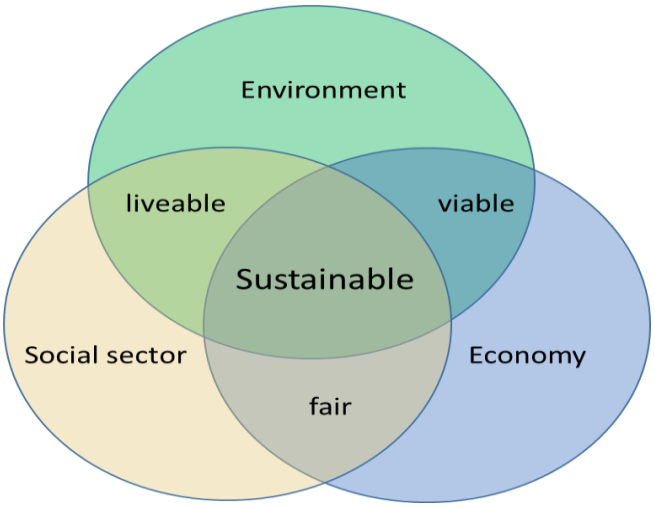

Figure 1: Venn diagram of sustainability based on its three pillars.

This diagram also allows us to situate the different interpretations of sustainable development according to the pillar or combinations of pillars on which they focus. The two most famous approaches are the techno-economic approach and the environmentalist approach, the two ends of the spectrum of approaches that attempt to reconcile the two visions [7].

In the techno-economic approach, the economic pillar is central and environmental problems have technical solutions that emanate from a prosperous economy based on "sustainable growth".

In contrast, the environmentalist approach, supported mainly by non-governmental actors, considers that "the sphere of economic activities is included in the sphere of human activities, which is itself included in the biosphere" [8] and that "natural capital" cannot be substituted.

The Sustainable Development Goals (SDGs)

SDGs address global challenges of poverty, inequality, climate, environmental degradation, prosperity, peace and justice. Adopted in September 2015 by the UN as part of the 2030 Agenda, they follow on from the 8 Millennium Goals which covered the major humanitarian challenges of developing countries for the period 2000-2015: The Millennium Goals had made it possible to reduce hunger and poverty, but had also shown their limits in terms of reducing inequalities because of their lack of transversality. Hence SDGs intend to overcome these difficulties by setting up a roadmap built on interconnected objectives. They define 17 priorities for socially equitable, environmentally safe and economically prosperous development by 2030 The OECD regularly produces reports with extensive econometric data [9] that measure progress toward each of these goals (fig. 2)

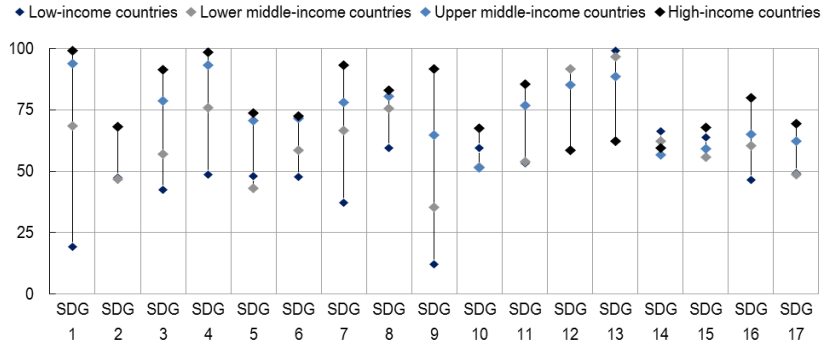

Figure 2. Percentage of progress towards SDGs in 2020, based on [9] and [10] using World Bank classification of countries.

In addition, each SDG is broken down into a number of targets that define priorities, actions to be taken as well as the means to achieve them. For example, SDG 12 insists on the need to halve global food waste by reducing food losses along the production and supply chains, which strongly implies the field of transport, in particular the food transport chain. SDG 12 also calls for rationalization of fossil fuel subsidies and phasing out of environmentally harmful subsidies. For the transport sector, this target is in line with the decarbonization imposed by the energy transition and climate action.

2.2. The place of road transport in the SDGs

An examination of the SDG target themes reveals that transport plays a key role in five of them: transport accessibility and connectivity, decarbonization, security, supply chain optimization and digital technology development. Moreover, a study of the occurrences of these target themes in each of the SDGs (Tab. 1) shows that, in addition to SDG 12, SDGs 7, 9, 11 and 13 are objectives in which transportation plays a major role.

SDG 7 requires doubling the global rate of energy efficiency improvement primarily concerns the transport sector whose final energy consumption of 2,891 MTOE represents 29% of global consumption in 2018 [11]. SDG 9 sets the goal of developing, reliable, sustainable and resilient infrastructure to support economic development while allowing affordable and equitable access for all. This concern is also present in SDG 11, which emphasizes the need to ensure access to safe, affordable, accessible and sustainable transport systems for all through the development of public transport and the need to reduce the negative per capita environmental impact of cities by paying particular attention to air quality. Finally, SDG 13 prescribes the improvement of resilience and adaptive

capacity to climate-related risks and natural disasters and the integration of climate change measures into national policies, which is particularly relevant to transport (Part 4).

Table 1. Presence of transport among the target themes of the MDGs

ODD	1	2	3	4	5	7	8	9	10	11	12	13	14	17
Transport accessibility and connectivity	X	X	X	X	X	X	X	X	X	X	X	X		X
Decarbonisation of transport						X	X	X		X	X	X	X	
Transport safety			X	X	X				X	X				
Optimisation of supply chains		X				X		X			X	X	X	
Digital technologies in transport				X		X		X		X	X	X		

Lastly, the study of the place of road transport in the SDGs also brings to light that the concepts most often associated with road transport are *resilience*, *climate change* and *energy transition*.

3. ROAD TRANSPORT, RESILIENCE AND SUSTAINABILITY

The emphasis placed on the resilience requirement by the SDGs invites an examination of possible definitions of resilience as well as its articulation with risk management and sustainable development in the road transport universe.

3.1. Definition and illustration of resilience

The seminal works on resilience have been conducted in the context of developmental psychology [12] and biology. This explains why a number of fundamental works on resilience [13] use medical concepts and vocabulary. Resilience has thus been considered as a dynamic process of successful adaptation to adversity following stressful circumstances in the context of developmental psychopathology where the two key elements of recovery velocity (called elasticity in this context) and malleability (proximity between the initial and the recovered state) have been introduced. These works have also made it possible to define recovery as the ability to bounce back and fully recover from a shock [13]as well as sustainability as the ability to go on moving forward despite adversity [14]. From these works emerges a vision of resilience that focuses on the homeostasis of a system and its capacity to return to an initial state. Thus, among the set of definitions applicable to the road world, the one proposed by Reeves [15] can be retained because it is particularly synthetic:

"Resilience is the ability to resist, adapt to changing conditions and recover positively from stresses or disruptive events, planned or unplanned, which we will call shocks."

Furthermore, the graphic illustration proposed by Bruneau et al. [16] in the field of seismology can be used to illustrate resilience through the evolution of the level of service of a system (infrastructure or network of infrastructures) following a shock (fig. 3). It uses the following notions:

-Pre-event performance or preliminary level: level of service provided by the transport system before the shock
-Shock: impact that has a disruptive effect on the level of service
-Robustness: the level of service that persists after the shock
-Recovery speed (elasticity): slope of the service level curve versus time
-Recovery threshold: the stable level of service achieved at the end of the dynamic resilience process
-Recovery time: time taken by the system to reach the recovery threshold
-Malleability: difference between recovery threshold and pre-event performance

This representation makes it also easy to illustrate the effects of the different actions or levers usually recommended to improve the resilience of a road network.

-*Infrastructure design and maintenance:* Improving the structural resilience infrastructures that make up the network through design, construction and maintenance results in an increase in the robustness of the infrastructure and, consequently, of the network.

-*Network design:* A network design that incorporates, for example, redundancy of an infrastructure or a subsystem increases the robustness of the network as well as its recovery speed.

-*Prevention of natural hazards (warning system, predictive management and protective structures):* When the shock is due to a natural risk, prevention allows to reduce the level of the impacting hazard, i.e. the intensity of the shock, and sometimes to eliminate it.

-*Risk management (crisis management and evacuation plans):* Efficient crisis management following a shock increases the recovery speed and decrease the recovery time.

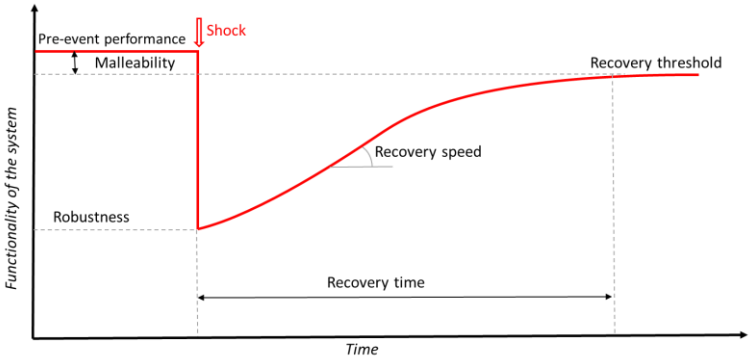

Figure 3. Illustration of the resilience of a system by the evolution of its functionality level following a shock.

3.2. Multiple shocks: sustainable or unsustainable resilience

The definition of resilience and the illustration presented describe the response of a system to a single shock. However the response of a system to repeated impacts is another important issue, whether to study successive shocks of the same nature or a set of shocks of a different nature but all related to a common cause such as climate change.

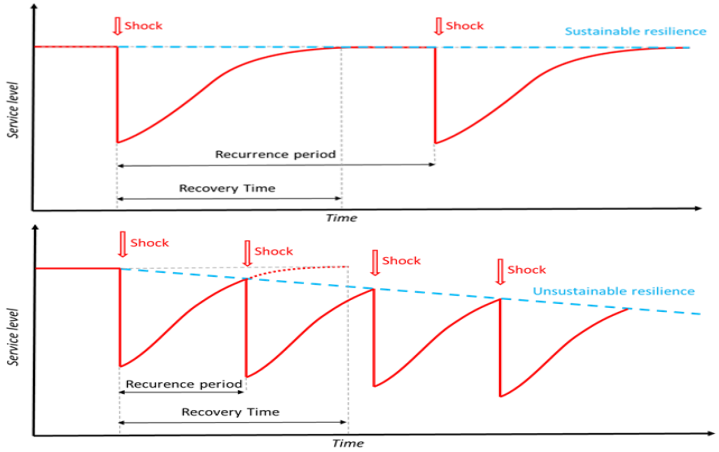

Figure 4. Simplified model of successive shocks on a system. Top, recurrence period greater than recovery time (resilience is sustainable). Bottom, recurrence period lower than recovery period (resilience is unsustainable).

In order to characterize the response of a system to multiple shocks, Dijkstra and Dixon [17] introduce the notion of sustainable or unsustainable resilience of a system according to whether or not it is able to maintain its level of service in the long term when subjected to a succession of shocks. They explain that sustainability of a system's resilience depends on the difference between the recurrence period of shocks and the recovery time of the system.

Indeed, while a long-term drop in service level may in theory be caused by a succession of service level drops due to the malleability of the system, in practice it is more frequent and damaging when another shock occurs while the system has not yet completed its recovery phase. This property can be illustrated using a simple model of a system with zero malleability (the recovery threshold is equal to the initial level) impacted by shocks of equal intensity at regular intervals called recurrence period (fig. 4).

3.3. Sustainability, Resilience and Risk Management

Resilience as a component of sustainability

For a system to be sustainable according to Blackmore [18], its design must take into account its vulnerabilities to disruption. Furthermore, since the objective of resilience is to maintain a primary objective (i.e. a level of service in the context of road transport) during and after one or more shocks, Bansal and Desjardine [19] show that resilience contributes to improve the sustainability of a system by helping it to absorb, recover from and adapt to economic, environmental and social disruptions. But there is one condition to fulfill: the primary objective must achieve an increased economic, environmental and social welfare goal.

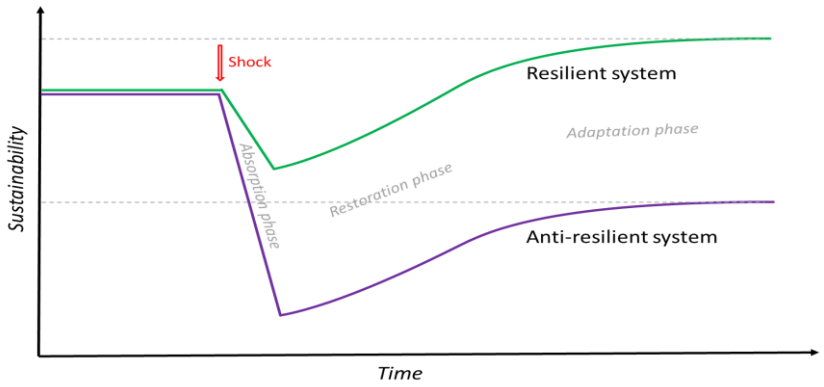

Figure 5. Resilience as a component of sustainability: Resilience as a process allows a resilient system to achieve a more sustainable functioning.

For the road transport sector this condition is largely met and as a result resilience is a necessary condition for sustainability. Nevertheless, it is not quite sufficient because increasing the resilience of a system makes it more sustainable while increasing the sustainability of a system does not necessarily make it more resilient [4]. Indeed, sustainability provides a system with goals while the concept of resilience is used among others to achieve those goals [20]. With the aim of quantifying sustainability from resilience, Walker [21] proposes a probabilistic risk analysis method and Jarzebski [22] takes it a step further by proposing

resilience indicators intended to measure economic, environmental, and social sustainability. Thus, when a system's resilience is failing it cannot claim sustainability because the adaptive component of resilience (as a process) has a determining influence on sustainability [23]: a resilient system can become sustainable after recovering from a shock while an anti-resilient system will have become less resilient (Fig. 5).

Resilience and risk management

The role of risk management in resilience studies is a central theme in works on resilience and sustainability, so much so that Linkov [24] identifies risk management as a subsection of resilience whose contribution to sustainability is critical. Saunders and Becker [25] conclude that risk reduction leads to increased resilience and sustainability based on case studies of risk assessment in earthquake-prone communities in New Zealand.

Furthermore, in the context of infrastructure management, it is widely accepted that risk management (gravity risk, flooding, fire, etc...) is an effective way to increase resilience by increasing the robustness of the system when subjected to shocks (3.1). Indeed, this depends on the intrinsic characteristics of the system such as the structural resilience of the assets that constitute it, but it also depends on the way in which the hazard associated with the risks has been assessed and protected against.

Finally, it is interesting to note at this point that most of the adaptation frameworks presented in (4.1), which are intended to increase the resilience of road infrastructure through adaptation to climate change, incorporate risk management approaches.

4. RESILIENCE, CLIMATE ACTION AND ENERGY TRANSITION IN ROAD TRANPORT

The concepts of resilience, climate action and energy transition are inextricably linked to the road transport-related targets of the SDGs (Part 2). This proximity comes from the fact that, in practice, the objective of resilience in road transport is related to the two main areas of climate action, adaptation and mitigation. Adaptation is an important issue for road infrastructure, while mitigation is more relevant for vehicles, whose evolution is driven by the energy transition.

4.1. Resilience of transport systems and adaptation to climate change

Political and economic aspects of adaptation to climate change

Adaptation to climate change refers to "all the changes in organization, location and techniques that societies [must] make to limit the negative impacts of these changes and maximize their beneficial effects" [26]. Adjusting the dimensioning of infrastructures to the expected changes in transport needs, moving infrastructures away from areas made floodable by climate change or protecting them against natural disasters triggered by climate change are common examples of adaptation actions.

Reactive adaptation, which is characterized by an ex post reaction to the impacts of climate change must be distinguished [27] from anticipatory adaptation, which consists of acting ex ante in order to reduce vulnerability to these impacts, limit their consequences or derive benefits from them. This distinction is essential in terms of public policy because the motivations for these two forms of adaptation are different. While reactive adaptation mobilizes resources to cope with events at the time they occur, anticipatory adaptation (like mitigation) mobilizes resources today to prepare for or benefit from possible future crises. The practical difficulty lies in the fact that public policy decisions are only easy to take after a crisis, whereas the cost of preventive actions is lower than that of reactive actions.

While climate change adaptation and mitigation are still widely perceived as a necessary evil that negatively impacts economic performance and growth, in many cases the resulting sustainability is economically efficient from the perspective of cost-benefit analyses.

Climate change adaptation and resilience of road infrastructures

Climate change hazards are a growing threat to transportation infrastructure. The need to improve the resilience of these infrastructures to the potential shocks of climate change hazards represents a major adaptation challenge that makes road resilience a necessary tool for climate change adaptation.

Since the beginning of the 21st century, some states have developed national plans for adaptation to climate change. This has led to the creation of adaptation frameworks that can serve as a matrix for different adaptation strategies. Thus, a number of recommendations and frameworks for Climate change adaptation strategies are gradually being proposed by states and international organizations. Some of them are specifically intended for road infrastructures, others are more general but can be applied to road infrastructures

As early as 2003, the UK Climate Impacts Programme (UKCIP) proposed a framework for the identification and assessment of risks from climate change based on available information, predicted impacts and adaptive responses. It is structured [28] in eight steps to support decision-makers in managing risk and uncertainty about the future impact of climate change.

In 2008, New Zealand produced an infrastructure management manual for communities [29]. This guidance manual provides a roadmap for assessing the effects and impacts of climate change, uses a risk assessment process based on the New Zealand Risk Management Standard, AS/NZS4360, and provides guidance for integrating climate risk assessment into local government regulatory, assessment and planning processes.

In the United Kingdom, the Highways Agency, in response to the risks induced by climate change to the trunk road network and the measures to be taken to mitigate them, produced an adaptation framework in 2009 [30]. This framework proposes a 7-step approach to identify how a number of activities (revision of standards, maintenance, development or operation of the core network, etc.) are affected by climate change, determine the associated risks and propose solutions to manage these risks.

In Europe, the RIMAROCC project (Risk Management for Roads in a Changing Climate, 2008-2010) has established a comprehensive approach to climate change adaptation for road infrastructure managers in Europe [31]. This framework proposes an 8-step method designed to be compatible with the risk analysis and management tools for roads used in the various European countries. It is intended to facilitate the production of risk management studies by or for road authorities following a method consistent with the ISO 31 000 standard on risk management. The CEDR project "Road owners adapting to climate change" (ROADAP) was launched in 2012 in order to produce a tool to prioritize adaptation and mitigation measures at reasonable costs. It retains the RIMAROCC framework for risk analysis and management and expands it into a series of 5 guidelines (on using climate data for current and future climate, the application of a QuickScan on climate change risks for roads, how to conduct a detailed vulnerability assessment, how to conduct a socioeconomic impact assessment, and on how to select an adaptation strategy) [32].

As concern for climate change adaptation is necessary at all stages of a project, the Asian Development Bank published a set of guidelines for climate-resilient investments in the transport sector in 2011 [33]. The guidelines provide a methodology to ensure that vulnerabilities are identified, adaptation strategies are appropriate and budget assessment plans are present and allow for revisions in road infrastructure projects design.

To enable transportation agencies to assess their vulnerabilities the US DOT published a framework for assessing vulnerability to climate change and extreme weather events in 2012 [34]. This framework, structured in three steps (defining the objectives and scope of the study, assessing vulnerability and incorporating the results into decision making) presents vulnerability assessment as an iterative process, updating and refining the need for climate information several times.

The U.S. Agency for International Development (USAID), which has been deploying significant climate change adaptation assistance since 2010, has been using a climate resilient development framework since 2014 [35]. This framework helps include climate change adaptation in the decision-making process about development by helping development practitioners identify, assess, select, implement, and adjust actions to reduce climate vulnerabilities and achieve sustainable development.

PIARC's International Climate Change Adaptation Framework for Road Infrastructure [36] was presented at the 2015 World Road Congress in Seoul. It provides practical guidance for road administrations to increase the resilience of their networks and structures. Focused on climate change adaptation, the Framework recommends that climate change risks and impacts should not be considered separately but combined: the combination of different natural and man-made risks and other forms of environmental, social and economic should be considered to assess the vulnerability of road infrastructures. The Framework underwent a review process during the 2016-2019 cycle [37], [38] and an update is expected for the World Road Congress of Prague in 2023.

4.2. Road transport resilience and climate change mitigation: objectives in line with those of the energy transition

The objective of resilience in road transport implies that it contributes to climate change mitigation, which is strongly linked to the decarbonization of energy systems, a central axis of the energy transition described in SDG 7.

Transport, which became in 2018 the sector with the largest final energy consumption, is also the fourth largest global emitter of greenhouse gases (GHGs), trailing only electricity, industry, and agriculture [11]. In 2018, it produced 8.5 GteqCO2 (14% of global emissions) while it emitted only 4.8 GteqCO2 in 1990.

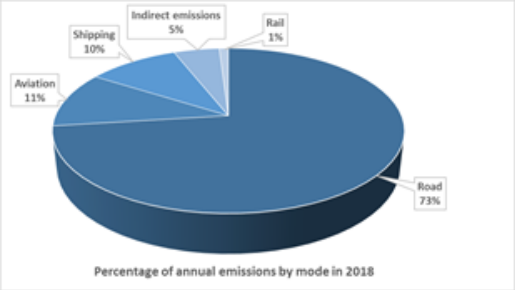

Figure 6. Global GHG emissions by transport mode in 2018.

The largest component of transport-related emissions is due to road transport, which alone accounts for 6.2 GteqCO2 or 73% of the total. Therefore road transport is the sector that represents the greatest opportunity for mitigation measures by being an important lever for the decarbonization goal [39]. According to Hidalgo and Huizenga [40], a low-emission scenario for road transport must include on the one hand policies that reduce the need for motorized travel through the promotion of alternative services that eliminate the need to travel, and on the other hand the development of new technologies such as electromobility or the hydrogen sector.

Moreover, decarbonization of road transport is closely linked to decarbonization of energy systems because the use of decarbonized energy resources is the main instrument for its success. According to forecasts [41], the energy mostly used by decarbonized road transport will be electricity, either for electromobility or for the production of fuels such as hydrogen, which requires anticipating an increase in the production of electrical energy and adapting the distribution networks to this new reality [42]. Thus, the most important innovations for decarbonizing road transport belong to the areas of electromobility or the hydrogen sector; they are also those that are most closely linked to the energy transition.

Electromobility.

The development of electric mobility is characterized by an increase in the number of light electric vehicles consuming between 20 and 30 kWh per 100 Km [43]. This evolution is strongly structuring the energy sector because the supply of electrical energy for all these vehicles represents two major challenges for electrical networks.

The first challenge is to ensure a sufficient supply to charge all these vehicles while increasing the share of renewable energies in electricity production. The second is the need to optimize and balance electrical systems to which a large fleet of small-capacity batteries (of the lithium-ion or lithium-

phosphate type) acting both like consumption points and storage possibilities, are connected for a connection time that can only be controlled to a limited extent.

The hydrogen sector.

The consumption of a light vehicle is estimated [44] at about 1Kg of hydrogen per 100 Km and the production of hydrogen by electrolysis from renewable energies requires between 50 and 60 KWh per Kg [45], not to mention the energy needs for water purification, compression or liquefaction of hydrogen and transportation [46].

Beyond production, the transportation of hydrogen is also a major issue for the sector insofar as the distribution network must be created. As the vehicle fleet is estimated to be too small and too dispersed in the short term, the use of pipelines would be too expensive. It is therefore envisaged to produce hydrogen locally, at the refueling station, from natural gas and electricity or to transport liquid or compressed hydrogen by truck. As liquid hydrogen has a higher energy density than electricity but is more expensive to produce, it is in this form that it will be used for large quantities over long distances, while compressed hydrogen will be used for the delivery of small quantities over short distances.

While waiting for the implementation of a network of supply stations that will allow us to consider the implementation of a fleet of light vehicles intended for passenger transport, road freight by trucks whose engines run on hydrogen is the first expected achievement of the hydrogen sector in road transport [47].

5. CONCLUSION: RISK MANAGEMENT, RESILIENCE AND SUSTAINABILITY

The study of the contribution of road resilience to the climate and energy challenges of sustainable development carried out in this work enables to present the notions of resilience and sustainability in the road world.

The topic of adaptation to climate change provides a practical illustration of the intertwining of risk management and resilience. Risk management articulates rationales based on known data and known unknowns (whose variability is easily identifiable). With resilience, we take a step towards the unknown to the point where it becomes necessary to mobilize adaptability by attempting to capture unexpected variables or events on which we cannot make effective predictions. These are the unknown unknowns, unpredictable future outcomes, events, circumstances, or consequences such as when, how intensely, and where the hazards resulting from climate change will manifest themselves. These include black swans, rare events that occur despite their extremely low probabilities of occurrence [25] and have catastrophic consequences.

Like Seager [48], who considers there to be a "spectrum of sustainability perspectives" of which resilience is one element, we have also shown that sustainability, which is inherently oriented towards future generations, goes beyond the notion of resilience in that it gives it the meaning of ensuring a liveable, viable and fair future. Therefore, the articulation of road resilience with risk management and resilience verifies the synthetic diagram inspired by the work of Saunders and Becker [25] represented in (fig. 7).

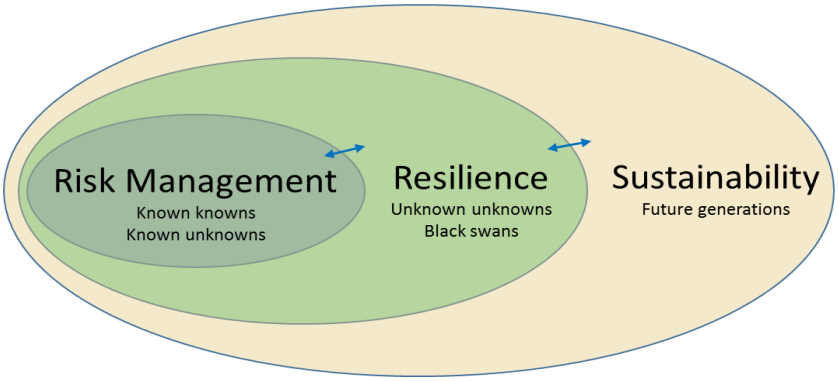

Figure 7. Risk management, resilience, and sustainability, from [25]

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