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Typology of the chains of causalities of environmental impacts in the transport sector

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Résumé
La plupart des évaluations environnementales ne tiennent pas correctement compte de l'ensemble des impacts sur l'environnement, ou utilisent des outils qui ne les représentent guère. Quels sont les impacts sur l'environnement ? Quelles en sont les caractéristiques ? Nous répondons à ces questions à partir du concept de chaîne de causalités, de la source à l'impact final. Les paramètres en sont : le type de source (construction de l'infrastructure, production du véhicule, production et distribution de l'énergie, trafic, et destruction du véhicule et de l'infrastructure), le processus lui-même décrit à travers les principales disciplines scientifiques impliquées, les échelles de temps et de distance de la source aux impacts finaux, le type de cible finale (nature : ressources et écosystèmes ; hommes : santé au sens restreint et bien-être ; patrimoine anthropique ; terre couvrant toutes les autres cibles). Cette analyse nous permet de définir 44 chaînes de causalités.

***Mots-clefs** : environnement, impact, typologie, source, processus, cible.*

1. Introduction

To build tools for assessing the impacts on the environment of a transport system or sub-system asks for a definition of the impacts on the environment, defined by final targets and modifications of target. For instance, the final targets of the traffic safety are mainly the humans with death and injuries. To assess each impact, the best way should be to measure the impact itself, by counting or evaluating for instance the number of people injured or dead because the traffic system. But such counting can't be made only *ex-post* and does not give any indication on the causes of the impact, because the impact cannot be linked by a one-to-one relationship with the accidents: the accidents are not the only causality of human death and injuries: local air pollution, greenhouse effect, hazards, among others cause death and injuries. The account of death and injuries due to the accident needs to take into account the process of accident. It is especially easy in the field of traffic safety, much more complex for most of the impacts.

For an evaluation *ex-ante* or for looking for the causes of an *ex-post* evaluation, a clear and precise relationship has to be established with the transport system. Each process, each chain of causalities from the source to each final impact on the environment has to be described in detail: in terms of sources, intermediate and final targets, mechanisms between intermediate sources and intermediate targets. Such description allows us also to express clearly what a potential indicator does measure and does not measure, and on which scientific mechanisms an indicator should be based. For instance the global warming potential evaluates the global temperature increase and not really the final impacts of greenhouse effect as sea level increase, the amount of fauna, flora and human habitat destruction, the food chain changes... The knowledge of the physical mechanism of the climate and temperature modifications as a function of greenhouse gas emissions allowed to build the shape of the indicator 'global warming potential'. At the same time, the description of the chains of causalities allows us to define quite precisely the term 'environment': What are the impacts on the environment? What are their characteristics or typical features? The most common presentation of the environment, especially by economists, considers it as a resource used by the humans for producing economic goods. This resource is an ecosystem, i.e. the association between a physicochemical and abiotic (the biotope) environment and a living community characteristic of the latter (the biocenosis), including fossil resources. This resource is destroyed but can be renewed at a given extend: the environmental issue is a question of resource stock, resource flow and capacity of the biosphere to support the effects of the human activities (carrying capacity): It calls the 7th principle of the Rio declaration (UNCED, 1992): "*...to conserve, protect and restore [...] the integrity of the Earth's ecosystem [...] the pressures their societies place on the global environment*". The pressure-state-impact (PSI) system from OECD seems well applicable to this meaning with a pressure representing a flow.

In parallel, the environment is often understood as the quality of our physical environment or the quality of life: a calm area with pure air and pure water, a beautiful landscape. (Job, 2005; Gudmundsson, 2007 for instance). It calls the first principle of the Rio declaration: "*Human beings [...] are entitled to a healthy and productive life in harmony with nature*". It is here often difficult to consider only flows or pressures.

These both meanings of the environment correspond roughly to the external and internal territory sustainability by Wackernagel and Rees (1999): the internal sustainability consists in protecting its direct environment and living area, but the external sustainability consists in protecting the world.

2. Precise list of environmental impacts

Such definitions are much too global and rough to be useful for describing the environmental issue or the impact on the environment of a human activity as the transport system, and for designing environmental impact indicators. An exhaustive list of the chains of causalities is necessary to present a full picture, especially if the explicit aim is to identify the most important issues (Black, 2000; Borken, 2003), and even to choose the issues of some importance for decision making (Ahvenharju et al., 2004; Nicolas et al., 2003; Zietsmann & Rilett, 2002): How to identify the important issues with a top-down approach without an encompassing assessment of all relevant impacts? But the definition of the environmental or ecological impacts is neither clear nor precise in the literature. The environmental impacts are often listed (USEPA, 1996; OECD, 1996; Swedish EPA, 1996; OECD, 2002; EEA, 2002; COST 350, 2002; Borken, 2003; Ahvenharju et al., 2004; Goger, 2006 or Goger & Joumard, 2007; Joumard & Nicolas, 2007), as in public surveys at national (Boy, 2007) or international level (EC, 20008). The lists are often heterogeneous, merging sources, intermediate states of the environment as local air quality, water quality, and final impacts on the environment as visual effects. For instance USEPA (1996) or Ahvenharju et al. (2004) list mainly the pressures or the first consequences of the transport system on the environment rather than environmental impacts (although designed as impacts). Beside some impacts quite always mentioned as climate change, photochemical pollution or noise, some others are rarely mentioned as soil erosion, vibration, light pollution, hydrologic and hydraulic risks, odours, soiling or visibility. Dimming and fire risk are not mentioned at all in the twelve references studied. Some impacts listed are very wide, merging several impacts on the environment, as air pollution or protection of soil and landscape. Goger (2006) or Goger & Joumard (2007) give the most precise list but only due to atmospheric pollutant emissions: In this field, impacts are distinguished when they are due to different chains of causalities, taking into account the fact that the impact categories shall together enable an encompassing assessment of relevant impacts, which are known today (completeness), but at the same time should have the least overlap as possible (independence).

In addition, the content of each chain of causalities depends on the society where it appends. Esoh Elame (2004) for instance show how the values and beliefs of the cultural heritage of given African peoples determine in a large extend the items of the nature they want to protect. Similar relationships had been shown by Roqueplo (1988) or Brüggemeier (2000) in the case of forests and acid rains in Germany. More generally Lammel & Resche-Rigon (2007) show how the concept of environment itself differs between holistic societies as Totonaque, Inuit or Badui ones and individualist / analytic societies as the western ones.

3. The concept of chain of causalities

We propose to enlarge the pressure-state-impact structure to the concept of process or chain of causalities between a cause and a final impact, with possibly a succession of couples cause-impact. A good example is the greenhouse effect with the greenhouse gases emission (GHG) as a first cause, which by physical phenomenon increases the earth temperature, which modifies the global and local climates, with impacts on the agriculture, sea level, with impacts on all the biocenosis including the humans. If an initial pressure can be easily detected (GHG emissions), there are afterwards a lot of intermediate states and impacts.

Another advantage of the concept of process or chain of causalities is to be much wider than a stock or flow problem inspired by physics: any process can be taken into account, as cultural, psychological, psycho-physical, biological effect, and of course physical. A chain of causalities can be described through:

- The element(s) of the transport system (or any other sector), which is at the begin of the process, taking into account the life cycle approach, ie. considering all the activities involved. Three main subsystems are involved (infrastructure, fuel, vehicle), and for each of them five types of activities (production, existence, use, maintenance, destruction). All together there are 13 subsystems-activities, as the use of the infrastructure, final energy and vehicle is considered common to the three subsystems (i.e. the traffic). The 13 subsystems can be simplified into four by considering the three main subsystems but extracting the traffic.

- The final targets: Goger (2006) and Goger & Joumard (2007) consider three targets (nature, humans, man-made heritage) and a pseudo-target, the earth. In addition the Eco-indicator approach (Brand et al., 1998; Goedkoop & Spriemsma, 2000) includes three types of endpoint damages: resources, ecosystem quality, and human health. The two first are subdivisions of the target nature. The (human) health is defined by World Health Organisation (WHO, 1946) as "*a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity*". Therefore it is useful to distinguish health in a restricted meaning (absence of disease or infirmity) and the complement so-called human well-being, because the processes are often very different. Finally we get a target structure with six targets: the resources, the ecosystems (both together the nature), the human health in a restricted meaning, the human well-being (both together the humans or the human health as defined by WHO), the man-made heritage, the earth.

- The in-between elements, i.e. the chain of causalities between the transport system and the final targets, to be described in detail. To design impact indicators, it is important to know the scientific milieu able to understand the process, and therefore to give the scientific disciplines involved. We propose a first and simple science structure: physics, chemistry, biology, psychology/sociology. It is important also to know if the process is linear or not, and if the transport system characteristics are major or minor explanation parameters, in order to know how these characteristics can be used for indicator building. Finally the reversibility is a major parameter from the sustainability point of view; The distance and time scales indicate who is concerned.

The whole picture disaggregates the different impacts found in the literature in order to understand the complexity of the processes involved, to identify the related sciences and to estimate the order of magnitude of the impact in space and time.

4. Typology of chains of causalities

According to this structure, a typology of the chains of causalities of the environmental impacts of the transport system is proposed Table 1 (without the elements of the transport system). 30 aggregated chains are distinguished, and 44 when taking into account differentiation in the last steps of the process corresponding to different final targets. The chains are independent and encompass all the relevant impacts found in the literature. The description of the chains could be more detailed, by dividing a chain into two or more chains, if it is considered as not homogeneous in terms of process or targets. In addition some chains can be missing.

A contrario, the aggregation of impacts is possible when the knowledge necessary to build impact indicators is similar and if the main characteristics of the chain are similar. As, to be practical, the number of categories should amount to a not too high number, and considering the importance of each impact and the availability of indicators, some impacts could be merged, or minor chains be deleted. Because it is important to give the possibility to further users to perform such simplifications, the chain structure has to be as detailed as possible: It is easier to merge and delete than to add processes.

5. Conclusion

To describe the environmental impacts of an activity as transport through a complete list of independent chains of causalities allows us firstly to give a precise definition of the term 'environment'. In the literature, the differences in the impacts considered translate often the research area of the author, and, when the work is more global, the local perception of the environmental or ecological issue. For instance the loss of visibility above the cities, due to air pollution, is often cited in North America, but never in Europe, although the physical situations are similar. It is especially important to define the term environment, when today the environmental issue is taken into account by most of the transport specialists without precise knowledge of this field: In this case the environmental issue is very often reduced to greenhouse gases or to few well known impacts, or are reduced unconsciously to impacts for which simple to use assessment tools are available.

According to COST 356 (Joumard, 2008), *an indicator of environmentally sustainable transport is a variable, based on measurements, representing potential or actual impacts on the environment, or factors that may cause such impacts, due to transport systems, flows or policies, as accurately as possible and necessary.* The precise description of the environmental processes constitutes then a powerful tool for indicator assessment, similar to but more completed than that done by USEPA (1996). *A priori*, it can be stated that the more to the right the indicator is, the more precise the final impact is. It is mainly a tool to define what precisely an indicator does represent: Does it represent the final impact, or an intermediate one? How accurately is the process translated into the indicator function? Which relevant impacts are not taken into account by existing indicators? Isn't it possible double counting?

When the aim is to design new indicators of environmentally sustainable transport, the knowledge of the process indicates which scientists should be asked about the best way to represent the impact. It is also a comprehensive basis to study the social perception of the environmental issue by survey, whom outputs can be used to balance the quality of local air, of regional air, noise, greenhouse effect… according to the focus placed on each of these impacts, as made for the Personal Security Index designed by the Canadian Council on Social Development (Tsoukalas & MacKenzie, 2003).

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Table 1: Proposed list of the main chains of causalities of environmental impacts with some characteristics. Target: R: Resource, ES: Ecosystem, H: Health, HWB: Human well-being, MMH: Man-made heritage, Earth.

Identifi-cation	reversibility, distance and time scale	Chain of causalities (states and processes) and *final impact* (main scientific disciplines involved: P: Physics; C: Chemistry: B: Biology; PS: Psychology / Sociology)		Target
Acidifi-cation	Mm, year	*(incl. secondary effect of photochemical pollution)* Emissions of NOx, SO_2, dispersion in atmosphere (P), possibly wet and dry deposition, chemical reaction (C) and therefore formation of acid compounds,	dispersion in air, water and soil (P), ecotoxicity on fauna / flora (B). *Decrease of ecosystem health, loss of biodiversity*	ES
			deposition on surfaces (P), chem. reactions with materials (C). *Loss of man-made heritage* (PS), *destruction of archaeol., classical or historic remains* (P), *loss of cultural legacy* (PS)	M
Direct toxicity	km, day	Emission of particles and air pollutants, dispersion in the atmosphere & water (P), sometimes dispersion in food (P),	*direct ecotoxicity on fauna and flora* (B)	ES
			direct restricted health effects (B)	H
Eutrophi-cation	10 km, year	Emissions of NOx, dispersion in the atmosphere & water (P), increase of plant biomass (B), *anoxia of fauna and flora* (B)		ES
Habitat fragmen-tation	practically irrev., km, year	Land take by infrastructure building,	cutting of the fauna habitat (B), l*oss of ecosystem health, loss of biodiversity*	ES
			cutting of the human habitat, *reduction of living areas of people* (B, PS)	HWB
Hydraulic changes	km, year	Land take, hydraulic changes, *modification of fauna, mainly, and flora habitat* (P, B)		ES
Land take	practically irrev., km, year	Land take by infrastructure building,	waterproofing of areas, *decrease of ecosystems (P, B), loss of biodiversity*	R?, ES
			waterproofing of areas, *loss of natural and wildlife protected areas*	ES
			waterproofing of areas, loss of available land for humans, *modificat. of outdoor recreation areas* (PS)	HWB
			destruction of archaeological, classical or historic remains (P), *loss of cultural legacy* (PS)	M
Soil erosion	km, year	Transformation of natural areas, *decrease of ecosystems (P, B). Loss of biodiversity*		ES
Biofuel agriculture	km, year	Agriculture for biofuels, transformation of natural areas, *disappearance of fauna and flora* (B)		R?, ES
Light pollution	Mm, min	Emission of light, modification of luminosity of the open space (P), modification of biota behaviour(B), *effects on biota health*		ES
Ozone depletion	earth, year	Emission of halogen compounds, dispers. in atmosphere (P), chemic. reaction (C) ozone layer depletion, UV in-crease on earth (P),	*ecotoxicity on fauna, flora* (B)	ES
			health effects (B)	H

Photo-chemical pollution	Mm, day	Emission of NOx, NMVOC, CO, dispersion in the atmosphere (P), chemical reaction (C) and therefore increase of photochemical pollutants as ozone,	*health effects* (B)	H
			loss of agriculture productivity (B)	R
			ecotoxicity on fauna, flora (B)	ES
			deposition on surfaces (P), chemical reactions with materials (C), loss of man-made heritage (PS), destruction of archaeol., classical or historic remains (P), *loss of cultural legacy* (PS)	M
			secondary effects: greenhouse gas, acidification	(ES), (M)
Non-renewable resource use	irrev., Mm, 100 years	Non-renewable resource use, *decrease of metals, fossil fuels availability for the future* (P)		R
Traffic Safety	partially irrev., m	Accidents, *human death, injuries* (B)		MMH
Non-recyclable waste	Partially irrevers. (nuclear w.), all	Waste disposal (incl. nuclear waste), dissemination in the nature (P), *impacts on health and ecosystems* (B)		ES, HH, HWB
Soil and water pollution	100 km, year	Emission of gaseous, liquid or solid pollutants, dispersion in the soil and water (P),	*ecosystem health* (B)	ES
			health effects (B)	H
			recreational areas forbidden (PS)	WB
Hydraulic risk	km, year	Risk of floods, *destruction of natural and human habitat* (P)		ES, MMH, M
Direct waste from vehicles	100 m, year	Waste thrown directly from the vehicles, accumulation. *Annoyance* (PS), especially if the landscape is of high quality		HWB
Techno-logical hazards	km to earth, day - century	Industrial accidents, incl. nuclear power plants. Dispersion in the atmosphere, soil and water (P), *biological impacts on humans and biota* (B)		ES, HH
Noise	km, hour	Emission of noise, diffusion, absorption or reflection by surfaces (P),	*disappearance of calm areas* (PS)	HWB
			annoyance for people (PS), *health effects* (B)	MMH, HWB
			ecosystem health (B)	ES
Intro-duction of non-native species	Earth, irrev.	Introduction of non-native species, small individuals, seeds… disperse and survive (B), modification of biocenosis, l*oss of biodiversity*		ES
Habitat disruption by wakes / anchors	km	Emission of wakes, microhabitat changes. *Loss of biodiversity, loss of ecosystem health*		ES
Biota collision	partially irrev., m	Fauna collision from small insects to big mammals or fish, damage by anchors. *Loss of biodiversity* (B).		ES
Fire risk	10 km, year	Fire ignition by sparks, matches… or accidents. *Destruction of natural and human habitat* (P)		ES, MMH, HWB
Odours	100 m, hour	Emission of VOC, dispersion in the atmosphere (P) at short distance, *sensitive pollution perceived by smell* (PS)		HWB
Soiling	100 m,	Emission of PM, dispersion in atmosphere (P) at short distance,		HWB

	year	deposition on surfaces (P), chemical reactions with materials (C), *sensitive pollution perceived by the sight* (PS)	
Visibility	100 m, day	Emission of PM and atmospheric pollutants, dispersion in the atmosphere (P) at mid distance, chemical reaction in air (C), *sensitive pollution perceived by the sight* (PS)	HWB
Visual qualities of landscape / townscape	practicall y irrev., km, year	Land use, infrastructure presence, *annoyance* (PS), especially if the landscape is of high quality	HWB
Vibration	100 m, hour	Heavy traffic vibrations, mass diffusion, *destruction of earth houses* (P), *annoyance* (PS)	HWB, M
Greenhouse effect	irrev., earth, century	Emission of air pollutants, dispers. in atmosphere (P), sometimes chemical reaction (C), creation of secondary pollutants, increase of greenhouse effect (P), climate change (P), sea level increase (P), *destruction or modification of habitat for fauna, flora and humans* (P), *change in food chain* (B), *economic losses* (PS)...	Earth
Dimming	100 km and earth, day to month	Emission of aerosols, dispersion in atmosphere (P), physical reactions (P) and sometimes chemical reactions (C), regional dimming, regional temperature decrease, global climate changes, *destruction or modification of habitat for fauna, flora and humans* (P), *change in food chain* (B), *economic losses* (PS)...	Earth