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IMPACT INDICATORS IN TRANSPORT INFRASTRUCTURES: A NEW MARKET FOR ENGINEERING DESIGN RESEARCHERS

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1. Introduction

Indicators are a very important guide in decision making since they translate knowledge into easy-to-handle information units. They can be used to measure and calibrate progress towards the improvement of sustainable development, as warning signals to prevent economic, social, and environmental damages, and as communication tools for ideas, thoughts, and values.

Transport is never environmentally neutral. Emissions from transport represent a very high share of the overall emissions: about 90% of all lead emissions, about 50% of all NO_x emissions and about 30% of all VOC emissions. Of this, about 80% of the emissions arise from road transport and more than 55% from private cars alone [Sorensen et al. 1999].

A number of international organisations have developed indicators for decision making regarding sustainable transport infrastructures (EEA, OECD, UNCSD, World Bank, etc.). Some of these indicators are emissions of greenhouse gases, ambient concentration of air pollutants in urban areas, number of fatalities related with the number of vehicles, etc.

However, indicator development for transport remains an open field for research in which engineering design methodologies such as life cycle assessment, life cycle cost and risk assessment may be applied to obtain new, more significant indicators of the state of transport infrastructures in a country or region.

The United Nations Commission on Sustainable Development (UNCSD) recognises that no existing set of indicators is final and definitive, but should rather be adapted to the specific conditions of each country, to their priorities and capabilities [Shah 2004]. They also recognise that further research in the development of vulnerability indicators -as would be indicators that reflect infrastructure response to weather phenomena- and promotion of research methodologies for indicator development are needed.

This paper aims to draw attention to a not very explored “market” for engineering design researchers, by discussing the current state-of-the-art of impact indicators for transport infrastructures and the possibilities of more representative results by means of engineering design methodologies.

2. Background

The publication “Indicators of Sustainable Development: Guidelines and Methodologies”, developed by the Commission on Sustainable Development (CSD) of the United Nations (UN) has been considered as the starting point for nations to develop their own national programmes using indicators that measure their progress towards sustainable development. Since then, other international

organisations like Organisation for Economic Co-operation and Development [OECD 2003] and the World Bank [2002] have also developed sets of environmental indicators.
The most complete scheme in order to organise information concerning sustainable development is DPSIR ("Driving forces-Pressure-State-Impact-Response"), which defines five indicator categories:

- D: Driving-force indicators, they are those factors that influence relevant variables like the number of vehicles per capita.
- P: Pressure indicators, describing variables directly causing environmental problems. For instance, CO_2 emissions.
- S: State indicators, showing the current state of the environment. For instance, lead concentration in cities.
- I: Impact indicators, describing the latest effects of state changes. For instance, the number of people affected by harvest losses due to climate change.
- R: Response indicators, showing the efforts of society in solving problems. For instance, gasoline taxes.

The DPSIR model is an extension of the PSR (Pressure-State-Response) model developed by Anthony Friend in the 70s and subsequently adopted by the State of the Environment (SOE) group of OECD.
An evolution of this scheme is the inclusion of the Prevention Principle, which since the year 2000 should be included in European Union policies, especially if the risk cannot be completely proven or quantified or its effects cannot be determined due to insufficient scientific information.
Other simplifications can be made on these five categories, as the aforementioned PSR model or the DSR (Driving forces-State-Response) model adopted by the UNCSD.
In Europe, the DPSIR scheme is used and the development of impact categories is shared between Eurostat (Statistical Office of the European Communities), focusing on the DPR model, and the European Environment Agency (EEA), leading on State and Impact (S-I) categories.
At a European level, there are several noteworthy research works on the development of transport infrastructure indicators:

- The report "Towards sustainable transport infrastructure" [EU 1996]. This report describes the situation of transport infrastructures and defines -with no methodological development- possible indicators for transport infrastructures: roads, railways, ports and airports.
- The Transport Sector Project developed by Eurostat and Joint Research Centre (JRC), based mainly upon statistical data [Sorensen et al. 1999].
- The "Transport and Environment Reporting Mechanism" (TERM) created by EEA to show the situation, the problems and trends in integration of transport in the environment [EEA 2001-2004].
- The "Transport Safety Performance Indicators" [ETSC 2001] developed by the European Transport Safety Council, applied to the transport safety domain.

3. Impact indicators

The EEA compiles the following impact indicators for the transport sector:

- Population exposure to above-standard air pollution levels
- Contribution of transport to air quality
- Exposure to noise and annoyance
- Transport accident fatalities
- External costs of transport

Of all these indicators, the one posing the greatest methodological problems is external costs of transport, since they are high and uncertain [EEA 2002]. The external costs of transport are those that affect society, and are not assumed by the transport user. These costs comprise:

- Environmental costs (e.g. damage due to pollution, noise, climate change, etc.)
- City barriers
- Non-covered accident costs (e.g. loss of working hours and productivity)
- Non-covered infrastructure costs

- Congestion (time loss)
- Landscape fragmentation, ecological separation, and land take

There is no unique, completely accepted methodology for estimating external costs. The most relevant studies are:

- ECMT [1998] measures external costs of air pollution, climate change, noise, accidents and non-covered infrastructure costs, but does not account for urban effects. Costs are determined only for road and railway transportation.
- ExternE [Friedrich et al. 2001], which accounts for energy-related external costs of transport, such as air pollution and climate change. It does not account for costs like congestion or accidents. The Impact Pathway Approach (IPA) technique is used, with which the impacts of air pollutants are quantified when modelling their emission and dispersion in order to calculate pollutant impact levels. The costs of the produced damages are calculated in relation to individuals' willingness to pay for them.
- Infras/IWW [2000] is the reference study by EEA. It does not account for congestion costs for any transport mode other than road transport.
- UNITE [Doll et al. 2000] is a project funded by the European Commission to unify accounting criteria and marginal costs of transport. The proposed methodology to determine external costs is based upon the IPA methodology developed in the ExternE project. Regarding the economic evaluation of costs, they conclude that further research is required.

Looking at European policies guidelines it is common to find –both at European and national scales- goals regarding the sustainable development of infrastructures, like reduction of global impacts on climate change, identification of sensitive areas, and externalisation of costs.

The use of just statistical data or data from field measurements, which is the current approach for the development of indicators, is not enough to reflect infrastructures conditions. A more realistic approach requires the development of impact indicators.

Life Cycle Assessment (LCA) can be useful when developing impact indicators, since it allows the determination of the infrastructures global impact on the proposed factors: climate change, noise, and land use regarding landscape fragmentation, ecological separation, city barriers and land take.

LCA is useful to evaluate the environmental load associated to infrastructures in normal operating conditions. However, the environmental impact and sustainability of infrastructures can be noticeably affected by accidental causes -for example, a road accident involving a truck carrying dangerous goods- or unlikely causes –for example, a railway embankment acting as a levee in a torrential rain scenario causing floods of the lower areas.

Risk assessment can be used to assess the vulnerability of infrastructures to accidental situations. Risk assessment can be used as a stand-alone methodology or in combination with LCA methodology to develop impact indicators. The integration of risk assessment and LCA methodologies allows a more realistic approach, considering not just normal operating conditions but also possible accidents.

Finally, both methodologies can serve as basis for economic assessment of external costs. As far as LCA is concerned, there exist a few methods, like Tellus and EPS, whose results on environment impact assessment are expressed in economic units.

Other option is to develop a methodology with two performance measures. Environmental performance is measured using a LCA approach, following guidance in the International Standards Organization 14040 series of standards for LCA. Economic performance is separately measured using the ASTM International standard life-cycle cost (LCC) approach. These two performance measures are then synthesized into an overall performance measure using the ASTM standard for multiattribute decision analysis [Lippiat 2002].

In order to show the potential of these methodologies in impact indicator development, their state of the art is briefly outlined in the following sections.

4. LCA for transport infrastructures

Life cycle assessment is a technique which allows to evaluate the environmental load associated to a given product, process or system, identifying and quantifying material and energy use and environmental waste. The study covers the whole life cycle of a product, process or system, including the following stages: extraction and processing of raw materials, production, transport and distribution, use, reuse, maintenance and waste elimination.

Back in 1994, ISO founded a technical committee in charge of the normalisation of several environmental management tools, including LCA. Up to date, four international norms have been published on the subject of LCA (ISO 14040-14044) for its methodological development.

The inventory phase of LCA is the most laborious one and it basically consists of compiling the different environmental impacts that the studied system has on the environment. Each stage or individual process is considered as a subsystem. For each subsystem, raw materials, secondary materials, energy used and environmental emissions are specified. ISO 14041 defines inventory analysis as the element of LCA that "deals with data collection and calculation procedures to quantify relevant inputs and outputs of the production system subject to study".

Life cycle inventories for transport infrastructures include data collection about energy and construction materials. Fossil fuels and electric power have been thoroughly studied from a LCA perspective [ETH 1994, Buwal 1996, etc.]. The interest in fuel comparisons has increased after the latest advances in biofuels and fuel cells [MacLean et al. 2000, Van Mierlo et al. 2003, etc.]. There are also life cycle inventories of construction materials [Intron 1997, Cardim de Calvalho 2000] and commercial databases, such as IVAM, Bees, Athenea, Spine@cpm, etc.

Impact categories are the effects caused by environmental aspects of the studied system on the environment. Adopting the list of categories defined by Guineé [2002], following a problem-oriented approach, the most significant categories are climate change, noise, and land take. It would be interesting, though, to include other categories like acidification and human toxicity given their relation with pollution due to the use of fuels.

The results of the inventory phase are classified within impact categories and an impact indicator is calculated for each category using characterisation factors. These factors may be elaborated starting from the values suggested by the Institute of Environmental Sciences (CML) of Leiden University [Guineé 2002], the Intergovernmental Panel on Climate Change (IPCC) [Houghton et al. 2001] and others.

This phase will yield an indicator value for a defined functional unit, for each impact category and for each transport infrastructure type. According to ISO 14042, it is unsuitable to group indicators of different categories under a single index. Furthermore, ISO 14042 does not allow the use of single indices on public reports.

Certain impacts like noise and land take pose greater methodological difficulties than other impacts like climate change or acidification. Regarding the noise category, Muller-Wenk [2004] proposes a procedure to determine health deterioration resulting from exposure to road traffic noise. Health deterioration is expressed as sleep disturbance or communication hindrance. This study has been applied to traffic in Switzerland and the Netherlands.

For the use of land category, Schenck [2001] presents a list of indicators on use of land and biodiversity currently under validation in the US. Vogtlander et al. [2004] introduce a new approach expressing impact in terms of changes in flora biodiversity and propose an indicator –eco-cost of land conversion- for marginal costs of prevention of negative impacts on biodiversity.

Several life cycle assessments focused on transport infrastructures are featured in the literature. About road construction, Mroueh et al. [2000] have elaborated a database to compare different alternatives on road construction and civil engineering works. Trelor et al. [2004] have applied a simplified LCA method based upon the energy category for road design and vehicle manufacturing, maintenance, disposal, and operation. Also using just the energy category, Bouwman & Moll [2002] have assessed different systems of land passenger transport.

Regarding railway infrastructures, von Rozycki et al. [2003] performed a LCA on the German high-speed train, ICE, that included manufacturing and maintenance of trains, construction, and

manufacturing of railways and buildings and impact during use. Ojan & Jean [1999] have performed LCA on the underground of Copenhague, including construction, maintenance and transport.
More frequent are LCAs focused on the environmental impact caused by different means of transport and based mainly upon fuel type and consumption.

5. Risk analysis

The risk-related indicator developed by the EEA is transport accident fatalities. The Directorate-General for Energy and Transport of the European Commission has pointed out the interest in road safety indicators for two reasons: to be able to monitor the progress in each country, and to compare the situation between countries. For the comparison of countries the following ratios based on socio-economic information have been suggested, such as:

- Number of fatalities/population
- Number of fatalities/length of roads network
- Number of fatalities/number of vehicles
- Number of fatalities/traffic (vehicles-km and/or passengers-km)

However, for the development of useful impact and vulnerability indicators for sustainable development of infrastructures, a more comprehensive approach to risks should be taken. Risks such as accidental scenarios in the transport of hazardous goods, floods due to linear infrastructures acting as levee in a torrential rain scenario, or traffic collapses due to adverse weather conditions (snow, avalanches, frost, etc.) should be taken into account.
In the last decades risk has been developed scientifically because of the impacts that natural or industrial disasters have on society, the territory, the environment, and the sustainable development. Risk is defined as the product of an event frequency (or probability) and a quantified magnitude of its effects.
Measuring risk, i.e. quantifying the risk level of a given undesired event, implies calculating the constituent factors of risk. Therefore, it entails:

- For the calculation of frequency or probability: analysing potential hazards of systems, identifying their initiating events, predicting the behaviour of the system, and estimating the probability of occurrence of undesired events.
- For the calculation of effects: estimating the effects of the undesired events, identifying the elements at risk (people, material goods, and the environment), and estimating the vulnerability (or potential damages) of the elements to the effects. These quantified damages can also be translated into a common unit, such as cost for society.

There are a number of methodologies in the engineering design field which are useful in the calculation of the risks mentioned before.
The effects of accidental scenarios in the case of hazardous goods, such as Boiling Liquid Expanding Vapor Explosion (BLEVE) or pool fire, are well typified and can be analysed by means of effects models [Van den Bosch et al. 1997]. The different possible scenarios and their consequences depend on the transported chemical, on the meteorological conditions, and characteristics of the place of occurrence. International organisations and national governments publish the number of accidents in the transport of hazardous goods biennially, providing details regarding the transported chemicals and the place of occurrence, as well as flow maps of transported hazardous goods annually and meteorological data. All these available data makes the events tree analysis methodology [AICE 1989] a suitable way to estimate the probability of occurrence of the different undesired events of the accidental scenarios in the transport of hazardous goods.
For the calculation of the effects and damages, the elements with high vulnerability to a given hazard are identified, and the effects for different probabilities (which correspond to different meteorological conditions) are calculated. To calculate effects produced by an accidental situation, support is found in the EFFECTS software developed by the Netherlands Organisation for Applied Scientific Research TNO. To analyse the damage of the effects on the vulnerable elements, several sources are useful: PROBIT functions which correlate percentages of people affected with exposure doses to a harmful

effect [TNO 1992], such as heat radiation; the DAMAGE software developed by TNO with implemented vulnerability models; and the Seveso II Directive [96/82/EC] that, even if not being compulsory for chemical transport, defines concentration thresholds for the definition of intervention and alert areas according to that can be used as a reference.
Flood hazard will take place in areas with high probability of flash rains. Flood extension and depth depend on the discharge magnitude and on the topographical configuration [UNESCO-RAPCA 2005]. The UN's Disaster Management Training Programme (DMTP) [Coburn et al. 1994] and the US Federal Emergency Management Agency'S (FEMA) guide 386-2 [2001] recommend realising flood depth maps in case of site parameters, and flooded area or water volume maps in case of event parameters. The UNESCO-RAPCA project develops a case study in which Geographical Information Systems (GIS) are used for flood depth maps drawing.
Given a flooded area, a water volume or flood depth, the inventory of vulnerable elements (buildings, people, natural areas, etc.) can be quantified following the guidelines provided in FEMA 386-2 [2001] and DMTP [Coburn et al. 1994].

6. Conclusions

In spite of the economic importance of transport infrastructures and their impact on sustainable development, decision-making has been based on the development of very simple pressure and state indicators, developed with statistical data and data from field measurements.
The impact estimation that infrastructures have on the territory, the environment and sustainable development should be developed with new impact indicators within the DPSIR scheme of indicators and coherently with international guidelines (UNCSD, EEA).
The methodological development of transport infrastructures indicators is a field that offers interesting opportunities for research to engineering design methodologies, such as life cycle assessment, life cycle cost, and risk analysis. The contribution of these methodologies in the definition and development of indicators has been scarce for the moment; however, the complexity of the impact of infrastructures demands a more comprehensive approach that could be provided by the integration of the three methodologies.
Of special importance is the development of indicators that measure the infrastructures impact on climate change, noise due to traffic, and land take, as well as the vulnerability of infrastructures to adverse climate conditions. These new indicators should integrate results from techniques such as life cycle analysis, risk analysis, and life cycle costs.

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