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COMPUTER SIMULATION OF TRANSPORT IMPACT ON ENVIRONMENT

Summary. The paper presents a computer simulation as an effective method for testing the impact of transport on the environment. It shows the concept of a simulation model that allows the integration of different approaches and methods used in the discussed context, pointing to the System Dynamics (SD) as a suitable technique to formalize the model. Simulation modeling in the SD convention allows for the simultaneous estimation of all impacts of transport on the environment in the dynamic approach.

SYMULACJA KOMPUTEROWA WPŁYWU TRANSPORTU NA ŚRODOWISKO NATURALNE

Streszczenie. Artykuł przedstawia symulację komputerową jako efektywną metodę badania wpływu transportu na środowisko naturalne. Zaprezentowano w nim koncepcję modelu symulacyjnego pozwalającego na integrację różnych podejść i metod stosowanych w omawianym kontekście, wskazując na Dynamikę Systemową jako odpowiednią technikę formalizacji modelu. Modelowanie symulacyjne w konwencji systemowo-dynamicznej umożliwia jednoczesne szacowanie wszystkich skutków wywoływanych przez inwestycje transportowe w środowisku naturalnym w ujęciu dynamicznym.

1. INTRODUCTION

Transport is one of the vital factors determining the regional, national as well as the world's economic growth. Efficient transportation system stimulates economies to grow, while at the same time its inefficient management can significantly hinder their capacity to flourish [41, p.7]. Traditional approach to transportation problems focuses first of all on the economics of transport systems and ignores their impact on the environment. Most methods which find application in the transport system analysis originate from such an approach. In the second half of the 20th century the world saw the unprecedented development of this sector, hence it has become necessary to see the problem from a more modern angle [11]. Not only has it dramatically affected the balance in natural environment of humans causing not only serious pollution of air, water and soil or increased noise levels but it has also deformed natural topography, devastated vegetation and endangered numerous animal species[1].

The gravity of transport related threats forced decision makers to take them into consideration in analyses that precede transport investment planning. There are diverse methods that are used to assess transport environmental impact: from simple identification of individual impacts to complex methods of predicting the investment effects on a given element of local environment[2]. A large number of criteria and their various implications that must be taken into account make the process very difficult. Some of the popular methods do not address many essential factors, or they are not accurate enough. Another important methodological problem is how to integrate the assessments made by different experts who use varying methods and how to present them so that they can be comprehensible to all the concerned parties (such as investors, decision makers and local communities).

In a modern approach to transport-related problems it is recommended to take into equal consideration the interrelated effects of the transport growth viewed from the perspective of its dynamics. As a result, the analyzed system becomes particularly complex thus coercing the application of specific research methods. In the authors' opinion the appropriate tool to test the environmental effects of transport is a simulation model built in the convention of system dynamics. Such a model provides complex information about all the predictable impacts in dynamic and spatial perspective [24, p. 60] and makes it possible to reflect the secondary effects resulting from the inner dynamics of the analyzed system.

The purpose of this article is to present the concept of a simulation model designed to test the transport environmental impact and built in the convention of system dynamics.

2. SYSTEM DYNAMICS SIMULATION IN THE ANALYSIS OF TRANSPORT PROBLEMS

Computer simulation has been for long now an elementary method to study particularly complex systems. To put it simply, it is a technique which can be used to imitate the operation of the whole system or to copy a certain situation by means of computer programs. The main goal of the simulation is to provide information about a real or projected system. This information can be used in the process of decision making concerning the given system. The computer simulation is a numerical method applied to experiment on certain types of mathematical models, which describe the long term performance of a complex system by means of a computer [37, p. 21]. This method has an advantage over the traditional methods applied in transport system analyses because it gives the opportunity to examine complicated processes taking place in the system and its environment both in time and space ([33, p. 54], [17, p. 88], [8]). The good points of the computer simulation make it attractive for those who tackle diverse problems of great complexity (see: [33, p. 254], [17, p. 88], [28], [8]).

A popular method of simulation modeling applied mainly to analyze problems that are poorly structured with many interlocking relationships among its components is the System Dynamics. It is a simulation technique developed by J.W. Forrester and his associates from the Massachusetts Institute of Technology (MIT) at the end of the 1950s and the beginning of the 1960 ([16], [6]). Essentially, Forrester proposed to think of the system dynamics in terms of feedback. According to R. G. Coyle's definition System Dynamics deals with the behavior of systems over time in order to describe: (1) the system through qualitative and quantitative models, (2) the reaction to feedback, and (3) to design appropriate feedbacks and steering methods [10]. System Dynamics gives the chance and basis to understand and examine all the mutual interrelations within the systems as well as to determine the character of changes in these systems over time. It has been founded on theories from several fields of science, hence it enables us to apply different modes of operation (including conventional methods of analysis) into a single complex system of methods.

[1] Transport has plenty of negative effects on the environment. We can divide them not only according to types, but also by their duration, geographical range and mutual interrelations. See more: [29], [48].
[2] See more about the methods: [25].

The construction of a system dynamics model is mainly based on identifying mutual causation among the individual elements of the real system. When building a model we use our intuition, the experts' knowledge and experience, the theory of the discipline relating to our problem and, finally, on data coming from observing the system behavior in the past.

System Dynamics is a popular practice, which is confirmed by a large number of reports presented at multi-panel international conferences that have been held annually for over 30 years by the System Dynamics Society[3]. SD has been successfully applied when studying problems related to natural environment or transport which requires the combination of approaches and methods (see: [20], [19], [5], [25, p. 101-117], [27], [34], [31], [23, p. 879-888], [15], [46], [9]). The method has also been employed in research projects dealing with transport, e.g. SCENARIOS [42], SCENES [43] or ASTRA [3], [4], and in integrated evaluations of various transport policies [49], [22], [44], [45], [4].

3. GENERAL IDEA OF A SYSTEM DYNAMICS MODEL ASSESING THE IMPACT OF TRANSPORT ON ENVIRONMENT

The general structure of the proposed simulation model to assess the environmental impact of transport is presented in Figure 1 and consists of three basic submodels:

- the submodel of traffic forecast,
- the submodel of environmental effects,
- the submodel of transport network.

In order to improve the effectiveness of the model construction the researchers often divide a complex problem into smaller parts [50], which are called submodels in this paper. They are parts of the model referring to individual segments of the simulated reality.

The submodels of the proposed simulation model are made of modules that not only are related with the environmental effects, but also help estimate on a long-term basis future traffic on the elements of road infrastructure that are being built or renovated.

The modules referring to natural environment use data coming directly from the modules responsible for e.g. average vehicle speed, descriptive elements of the transport network, etc. which, in turn, require information computed in other modules as well as information about planned investment variants included in a separate module (see the interrelations in Fig. 1).

Each of the modules is presented by means of a suitable graphic symbol. Graphic symbols depend on a tool, by means of which the module has been created. In this paper the authors decided to apply Vensim DSS simulation package, which has been specifically created for the purpose of modeling in the SD convention.

The proposed model is constructed according to the concept of modular modeling which is based on the assumption that system modeling means creating „the model of models", i.e. a heterogeneous structure consisting of many repeatable structural blocks called *modules*[4]. Modules are small repeatable blocks written in a system-dynamic convention that reflect some parts of the real system, which have been considered elementary. The blocks contain the elements of the system-dynamic notation (levels, streams, ancillary variables, parameters) and the instructions of a formal simulation language (DYNAMO, VENSIM, Powersim, IThink etc.). Therefore, the module can be identified as the simplest possible simulation model, i.e. the model which reproduces single elementary actions distinguishable in the real system on the lowest of the examined hierarchy levels. The modules are the building material for constructing the target model, but they can be models themselves. In addition, the modules happen to be reproduced many times in one simulation model. The set of modules used to constructing the model can expand as new interrelations in the observation base are being found and the theory on the examined system is being developed.

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[3] See more://www.systemdynamics.org/.

[4] See more on modular modeling in e.g.: [26]; [28].

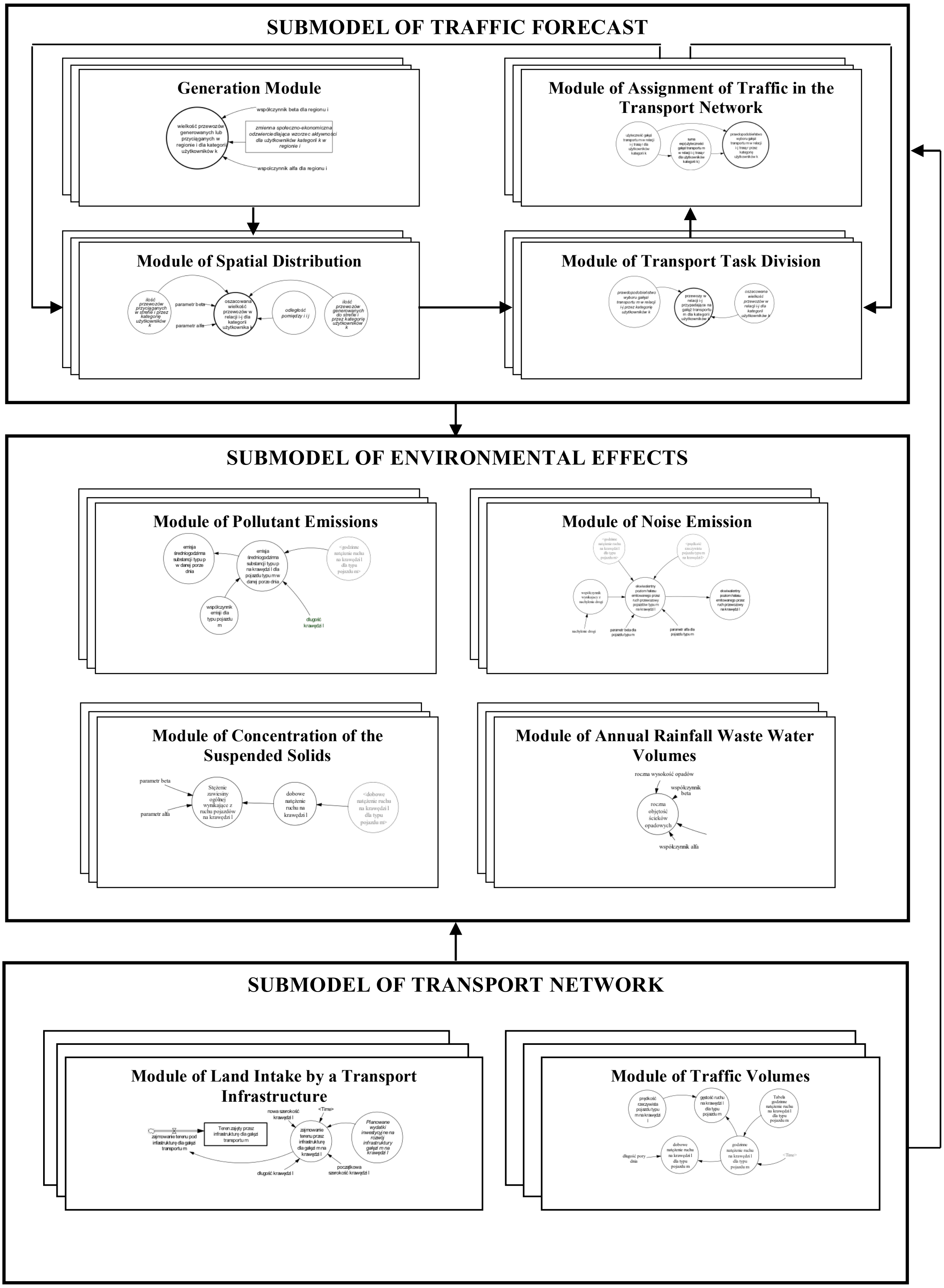

Fig. 1. The general structure of the simulation model assessing the impact of transport on the environment with module examples

Rys. 1. Ogólna struktura modelu symulacyjnego do oceny wpływu transportu na środowisko naturalne z przykładowymi modułami

With regard to its subject matter the concept of modular modeling the grounds for its application can be found in the analysis of the existing transport system models built in the convention of System Dynamics[5]. Additionally, this concept makes constructing and modifying the model quick and easy, hence more efficient and effective due to the opportunity to use ready-made modules that describe previously verified behavior patterns.

4. EXEMPLIFICATION OF THE MODEL FOR A CASE STUDY

In order to illustrate the applicability of the presented concept for the study into the environmental impact of transport the authors created a simulation model for a specific case study, i.e. for a ring road being a segment of the route 10 circling Stargard Szczeciński. The investment included the construction of the ring road, redevelopment of the local road network and the development of facilities reducing the negative environmental impact of the investment. The analyses took into account two options: (1) the Northern Option – the road would circle the town on the north (km 40+402.19 to km 54+240), (2) the Southern Option (recommended by the investor) – from the Lipnik junction to the Święte junction (km 40+402.19 to km 53+920); and (3) the Zero Option leaving the situation unchanged. In accordance to the *Act on Environmental Protection* and the Section 2, item 1, point 29 of the Regulation of the Council of Ministers on defining the types of investments that can significantly affect the environment and on detailed terms of eligibility of endeavors for reports on their environmental impact (Dz. U. no 27, item 2573 with amendments) the ring road of Stargard Szczeciński was qualified as an environmentally harmful investment. Therefore it was necessary to perform the assessment of its effects on the environment. For the purpose of constructing the model exemplification the authors used data and information from the related documents. The documents included:

- report on the environmental impact of the ring road of Stargard Szczeciński being a segment of the route 10 from the Lipnik junction to the Święte junction [38],
- the post-investment analysis concerning the protection of local developed areas from noise [2],
- environmental monitoring [35].

The simplified structure of the model exemplification is presented in Fig. 2. It shows the system of modules which have been used to run the simulation. It should be noted that this system is replicated in the target model on each of the edges of the transport network included in the investments and some of the modules appear in the system several times on one edge. What is more, it is obvious that the choice of modules to be included in the target model depended on the availability of data.

Table 1 shows the system of equations in the Vensim DSS notation for the module exemplification (the noise pollution module). It has been constructed on the basis of noise pollution models used when estimating noise levels to be emitted by the forecasted traffic[6]. The primary module equation is expressed in a mathematical form[7]:

$$L_{l,m} = \alpha + \beta \cdot \log_{10}(v_m) + 10 \cdot \log_{10}(q_{l,m}), \quad (1)$$

where: $L_{l,m}$ level of noise pollution emitted on the edge l for the vehicle type m in dB(A); $q_{l,m}$ traffic volume on the edge l for the vehicle type m; v_m mean velocity for the vehicle type m; α, β function parameters for the vehicle type m.

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[5] Synthetic description of several system-dynamic models of transport systems can be found in [27].
[6] See more on the methods of noise pollution assessment in: [13], [32].
[7] Derived on the basis of: [36, p. 19] oraz [39, p. 3].

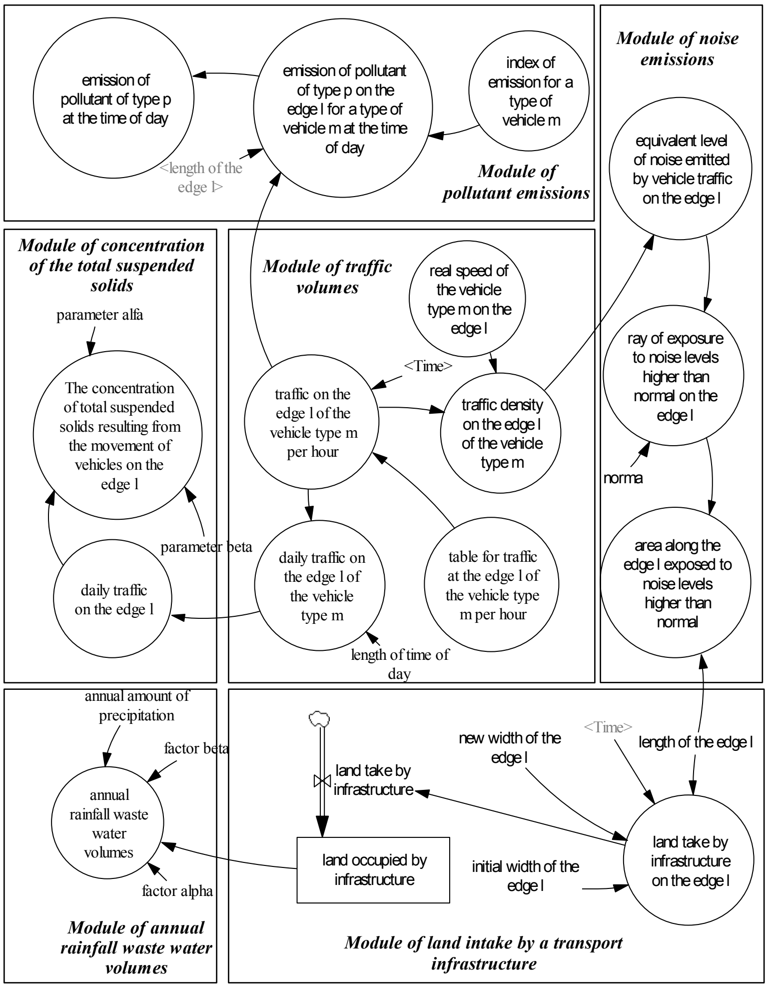

Fig. 2. The example structure of a model assessing the environmental impacts of transport
Rys. 2. Przykładowa struktura modelu oceny wpływu transportu na środowisko

Table 1

System of equations of the noise pollution module in the VENSIM DSS notation

Name of variable	Equation
area along the edge l exposed to noise levels higher than normal	length of the edge l*ray of exposure to noise levels higher than normal on the edge l
equivalent level of noise emitted by vehicle traffic on the edge l	12.8+19.5*LOG(real velocity of the vehicle type m on the edge l [edge, vehicle type, time of day],10)+10*LOG(traffic density on the edge l of the vehicle type m [edge, vehicle type, time of day], 10)[8]
norm	określona przez decydenta [9]
ray of exposure to noise levels higher than normal on the edge l	(equivalent level of noise emitted by vehicle traffic on the edge l-norm)/5.2[10]

Note: the values of such elements as: "length of the edge l", "real velocity of the vehicle type m on the edge l" and "traffic density on the edge l of the vehicle type m" are computed in separate modules.

[8] Value of the parameters α *i* β on the basis of: [36, p. 19].
[9] Acceptable noise levels in the environment are defined in: [40].
[10] On the basis of: [7, p. 41-43] and [14].

Fig. 3 presents the graph exemplification obtained in the course of an experimental simulation run by means of the Vensim DSS package. It shows the values of the primary noise pollution variable, which is the „equivalent level of noise emitted by vehicle traffic on the edge l” in case of the implemented investment option, i.e. the Southern Option, while the traffic forecast was determined in the „module of traffic volumes” basing on the assumptions adopted in the documents mentioned above.

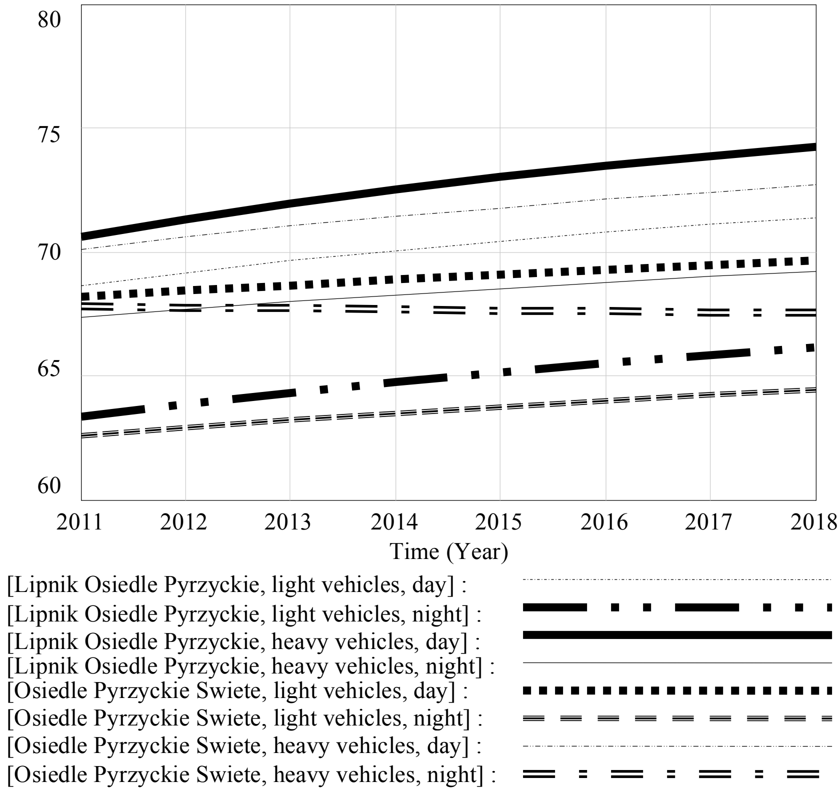

Fig. 3. Equivalent level of noise emitted by vehicle traffic on the edge l (in dB(A))
Rys. 3. Ekwiwalentny poziom hałasu emitowany przez ruch przewozowy na krawędzi l (w dB(A))

Comparison of data generated during the experiments with real data enabled the authors to conduct the initial model verification by means of qualitative tests[11] consisting in visual comparison of the simulated data with the available real data found in the report on the environmental impact [38]. The test results are promising. It is necessary to supplement the qualitative tests with quantitative ones where the accuracy of the simulated data will be measured. In this case it is recommended in the related literature to apply various measures of the model consistency[12]. However, because the purpose of this article is to present the applicability of computer simulation for testing environmental impact of transport the authors are not going to examine thoroughly the problem of model verification and validation.

5. CONCLUSION

Owing to the fact that it is based on modular modeling the presented concept of a system-dynamic model for assessing the environmental impact of transport provides the opportunity to integrate a range of methods and models designed for the same purpose and makes it possible to evaluate

[11] See more on qualitative tests applied during the verification of system-dynamic models: [47].
[12] See more on the model consistency measures in: [18].

simultaneously all the effects in the dynamic approach. In the proposed model the mutual relations (direct and indirect) between individual variables are taken into consideration, thus reflecting the inner dynamics of the examined system and, at the same time, determining the values of all the effects that have been looked at in the analysis. The concept of modular modeling where ready-made structural blocks are used in the process of modeling and stored in a library of modules can be further developed to form a simulation system understood as a generator of simulation programs. Such a generator can include, apart from the library of modules, a data bank, a bank of modules and a bank of methods. So understood computer simulation system additionally equipped with the user's graphic interface would become a perfect tool to examine the impact of transport on the natural environment[13].

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[13] The project was financed with the NCN funds allocated according to the decision DEC-2011/01/B/HS4/05232.

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