Reliability, safety and efficiency - challenges for transport infrastructures

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Abstract: *Transport infrastructure brings together conventional groundwork and innovative technologies in order to improve various aspects of transport system management and control. It enables anticipatory maintenance, planning and scheduling, resource management and aims to improve reliability and safety, increased capacity and asset utilization, better energy efficiency and lower emissions, higher customer service levels and increased economic feasibility. Transport infrastructures have long service life and great costs of building, manning, operating and maintaining throughout their life. Innovation and technology shifts proved to be important factors determining great changes in infrastructure potential and even determine its obsolescence. It is regarded as a concern throughout infrastructure's entire life cycle and reflects changes in expectation regarding performances in functioning, safety and environmental effects.*

Performance and failure are illustrated conceptually and represented in a simplified form considering the evolution of technology, the influence of innovation breeding new generation rail infrastructure, all the way through infrastructure's service life.

According to the identified particularities, recommendations are to be made in order to insure a best practice in lifecycle management and transport infrastructure renewal in the context of improved reliability, safety and efficiency.

Keywords*: TRANSPORT INFRASTRUCTURE, RELIABILITY, SAFETY, EFFICIENCY, LIFECYCLE, OBSOLESCENCE*

1. Transport infrastructures and their lifecycles

An unquestionable feature of transport infrastructures is the long service life. Even if some parts/ components decrease their performance more rapidly, most transport infrastructures last for decades, some even for centuries ((see Fig.1.1). Commonly, the lifespan of transport infrastructure is different than the physical life. The end of physical life is reached when parts/components are over the limit and need to be replaced, it doesn't depend on the demand level, economical factors, new technology boosts or on infrastructure obsolescence that is directly connected to increased pressure and level of expectations regarding performance measures.

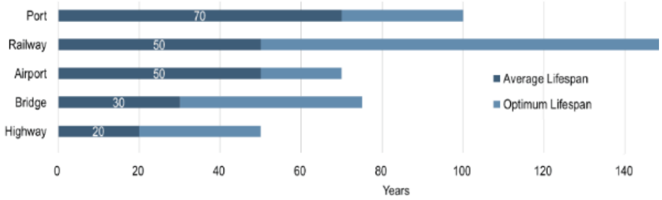

Fig. 1.1 *Main Transport Infrastructures Lifecycles*

(source: data from Living Planet Report, 2006 and Summary result of second Eurostat questionnaire on CFC on public infrastructure, DOC.CFC 15, Eurostat, 2003 [1])

Experience and testing are the two main sources of information on which the expectations on the service life of an infrastructure are based. Efforts to predict service life, as well as the form of function that describes performance deterioration, face a number of obstacles, including the limited ability to understand how failure occurs, uncertainties and factors influencing deterioration and lack of data are very complex issues of the problem. Among these aspects are the challenges of characterizing the service life for a facility, for the entire infrastructure or even for the entire system, as opposed to their repairable or replaceable elements.

In general, the experience already gained in good practice cases and the empirical data are still the main source of estimating the service life of an infrastructure. The decisions of designers and future infrastructure managers are based on the premise that performance at an appropriate level can be ensured for a certain service life - a convenient number of years. In some cases, financial reasons, rather than those of a technical or organizational nature, are the source of this lifespan. It can be said that the attempt to determine a correct theoretical value, which would predict the physical life of an infrastructure, is irrelevant, that this may even be impossible, at least at the level of the entire specific transport infrastructure.

First of all, the premises from which the forecast starts, for example, the characteristics of transport infrastructure features, the maintenance operations that will be applied, the future atmospheric conditions, cannot be guaranteed for several decades. Second, infrastructures are very rarely completely taken out of service; this does not happen until an alternative infrastructure is available to provide the same services, possibly at lower costs, or until the service is no longer needed, i.e. the infrastructure is obsolete. Maintenance work may be negligible, but component repair and replacement work must be carried out when it can no longer be postponed. In the end, the expected increases in users will more than likely lead to a decrease in the level of intrinsic performance of the old infrastructure below an acceptable minimum and then to its consideration as exhausted.

In conclusion, the notion of design service life of an infrastructure is significant only if it is defined in the sense of obsolescence and can hardly be described in terms of intrinsic deterioration of performance. Therefore a function of user's expectations must be included in the analysis [2]. The function P^F is known as „expectation function". The growth rate of this function of expectations can vary very rapidly, as shown in Fig. 1. 2.

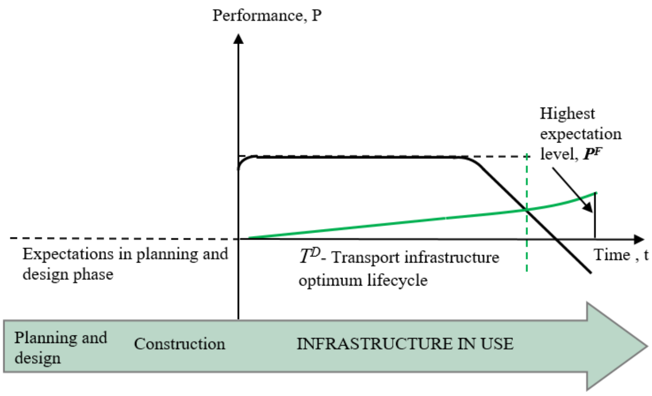

Fig. 1.2 Evolution of expectations over transport infrastructures

Expectations on transport infrastructure performance are rising, so the slope of the function curve must be greater than zero. Well-founded data for an analysis of this function are not easy to find, it is only known that the obsolescence of an infrastructure is determined by technological changes, new regulations, social, economic, user behavior and values, changes that are, as shown in the last decades, accelerated for periods of time comparable to the service life of the infrastructure.

Experience shows that expectations almost always have an increasing trend, but there is not much information either about the pace of growth or their consequences on the installation of obsolescence of infrastructure. Direct observation provides some information about each of the four main sources that induce the moral degradation of infrastructure: technological, regulatory, socio economic and behavioral.

Of these, technological change follow-on new generation, intelligent infrastructure that brings together conventional groundwork and innovative technologies in order to improve various aspects of transport system management and control, can only be seen from a long-term perspective and it is observed that it takes longer and longer until an infrastructure is considered obsolete. This period of transition from one technology to another is not as slow as it used to as there is currently a major technological change in transport sector.

2. Performance and failure

2.1 Performance

Infrastructure performance is a concept widely examined over the years and therefore many perspectives concerning this concept emerged. Present paper refers to the model of describing performance proposed by Lemer [3, 4] and bases his assumption on the mathematical formalization presented in equation 2.1.

$$Performanta = P(S_j, D_j, t) \qquad (2.1)$$

Where:

S_j represents the supply vector for an infrastructure facility *j (*in relation to to different users: operators, individual users, neighbors of the infrastructure);

D_j = the demand vector for an infrastructure facility *j* (in relation to different users: operators, individual users, neighbors of the infrastructure);

t = time, measured from the commissioning of infrastructure

On general terms, supply vector, S_j, is well described using a function that uses as variables the physical characteristics and operational characteristics of a given infrastructure, as in equation 2.1.

$$S_j = S(X_j) \qquad (2.1)$$

X_j represents the physical characteristics and operational characteristics vector (for example: simple or double track, interlocking systems type, management system type, safety integrity level).

The service outputs that infrastructure provides can be quantified as positive: higher accessibility, mobility, safety, comfort reliability or as negative: higher noise level, pollution, disruption of wild life habitats.

The main measures of the performance function, *P*, can be considered to be: reliability, safety and efficiency. Consequently, the specific criteria can be organized in three main groups: reliability criteria, safety criteria and efficiency criteria. Each group is multidimensional and the specific indexes varies with infrastructure's location, features etc.

Reliability. On general terms, reliability is a probabilistic measure of rail transport infrastructure network that refers to specific infrastructure elements ability to fulfill their roles, not to fail or malfunction, during a specific period, given a set of performance guidelines. Even if some elements of transport infrastructure fail, the network should remain functional even if not so performant as before. There can be differentiated three types of reliability [5, 6]:

- *Connectivity reliability* – the probability that the nodal infrastructure remains connected through linear infrastructure (links) - there is still a path connecting the nodes even if a set of links do not fulfill their roles or have been cut off;
- *Travel time reliability* – the probability that a trip between an origin and a destination node can be completed within a given time period. The travel time can be affected by the increasing demand for rail services, straining the existing system and therefore requiring optimization of the existing passenger and freight schedules to achieve increased throughput on existing rail infrastructure;
- *Capacity reliability* – the probability that an infrastructure network can accomplish a given level of travel demand and the reserve capacity can accommodate the required demand for a specific capacity loss due to network degradation or obsolescence Rail companies are increasing asset utilization and making significant investments in infrastructure to meet the capacity challenge.

Safety and Security. As rail network infrastructures become an even more attractive alternative to other modes of transportation, stricter requirements are being imposed on railroads to help ensure safety. Political scrutiny and regulatory oversight are increasing, with legislation enacted requiring positive train control (PTC) systems. Predictive maintenance and data analysis is being used for accident prevention.

Operational Efficiency. Aging rail systems limit the efficiency of resources and compromise reliability in established rail markets. New markets have the opportunity to adopt newer, more flexible technology infrastructures, advancing fast and leaving behind current practices. Many current intelligent transportation systems are old and complex, making the sharing of data difficult. They are also unable to cope with the scale of growth predicted over the next few years. Frequent network failures and systems components obsolescence can have a domino effect, significantly impacting customer satisfaction.

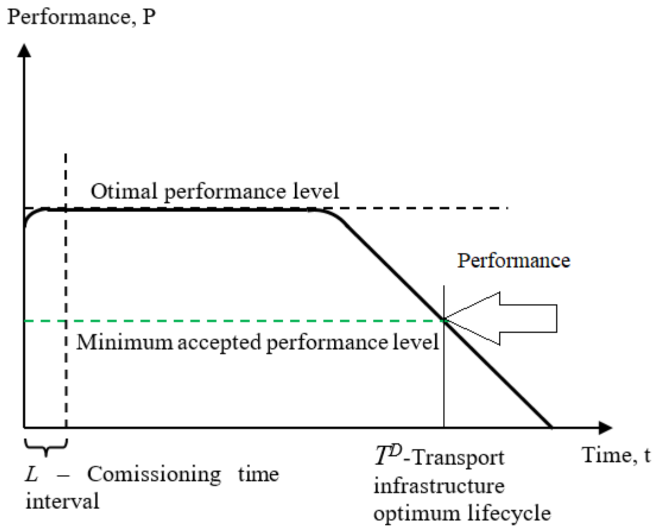

Fig. 2.1 Transport infrastructure performance evolution

Fig. 2.1 presents, in a simplified manner, the infrastructure performance function over its entire life cycle. At commissioning moment, typically, performance level is below optimum designed level. Most of real life situations show that a short period of operating infrastructure is compulsory in order to reach the optimum designed level of performance. For simplification in figures 2.1 is made the assumption that optimal and minimum accepted performance levels are stationary most of infrastructure's lifespan.

A special attention to operational matters must be shown in the early stage after commissioning the infrastructure in order to reach the highest level of performance and to avoid the possibility of early manning problems that can influence performance.

Assuming that infrastructures performance level is reaching the optimum designed level, the new infrastructure will continue to function at this parameters, in a quasi-stable regime, for a long period of time, if maintained according to standard procedures. A slow but inevitable degradation sets up as years go by reaching, at a certain moment an unacceptable performance level.

Planers and designers of infrastructure work with multiple criteria decision models trying to well balance reliability, safety and efficiency outputs in order to maximize performance for the entire infrastructure's design life, as in equation 2.4.

$$t \le T^D, P(t) \ge P^F \qquad (2.4)$$

Where T^D represents the infrastructure's design service life.

Maximum performance, in this context, denotes that level of service that insures reliability and safety at minimum acceptable cost, in other word, at the higher efficiency level. Considerations can be debated on this subject as different users consider that this minimum cost measure conveys in an unacceptable level of congestion, an unsafe service or other compromises.

2.2 Failure

Failure establishes when performance level drops below a threshold level considered by the decision makers to be inacceptable – infrastructure is either unable to fulfill its functions either shortly it will become unable, either is much too expensive to further operate it. The failure condition is described in equation 2.3:

$$P(t) < P^T \qquad (2.3)$$

Where P^T represents the minimum infrastructure's performance threshold level considered by the decision makers to be acceptable.

As for mechanical and electrical components, the failure behavior of infrastructure facilities can be described in terms of a bath-tub time-dependent failure (see Fig. 2.2). We can set the limits of three zones in this figure as those correspond to the young age, to the maturity and to old age, with decreasing, constant and increasing danger of collapse, respectively.

The effects of infrastructure components aging are compensated by maintenance actions, performed periodically, which reestablish the infrastructure performance level. In practice, during the interval between maintenances, the failure rate increases only slightly so that, to simplify the calculations, they are characterized by stepwise constant failure rates whose values are determined by imposing that the probabilities of failures within each maintenance period [6]. Even with maintenance counterbalancing its effects, the aging of some components is inevitable [7, 8].

As shown in practice, the result of a repair action on an infrastructure component might not necessarily return it to an "as good as new" condition since it is likely to become more instable and susceptible to future failures [9].

Negligence in respect to manning conditions of every infrastructure component and high solicitations of this components lead to an increased failure rate and therefore to a decreased performance level, resulting in a drawback of infrastructure's design service life.

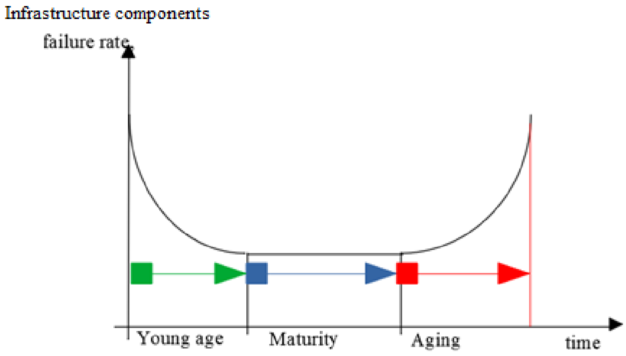

Fig. 2.2 *Typical behavior of infrastructure components failure rate. Adaptation after [10]*

3. Obsolescence of transport infrastructures

User's awareness, higher expectations due to innovation and technology shifts proved to be important factors determining great changes in infrastructure perceived performance and even determine its obsolescence. It is regarded as a concern throughout infrastructure's entire lifecycle and reflects changes in expectation regarding performances in functioning, safety and environmental effects. From the point of view of railway infrastructure management the problem of obsolescence is becoming more and more acute. Obsolescence has the connotation of the loss in value of one or more infrastructure's components, due not to its conditions or past operation history but to a change in the external scenario of technological evolution and marketing [11].

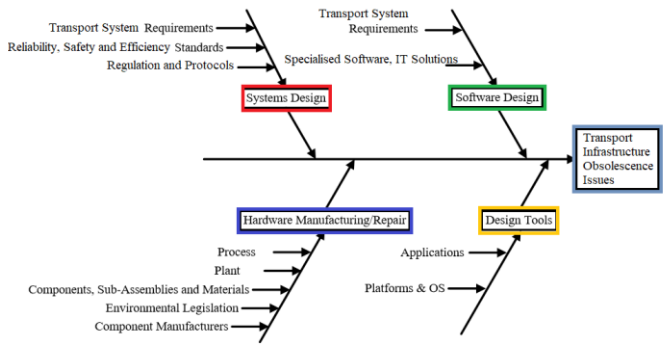

Fig. 3.1 *Transport infrastructure obsolescence fishbone diagram*

Fig. 3.1 shows that many stakeholders cause or are affected by obsolescence. The transport infrastructure depends primarily on the fixed facilities, their components and on supporting tools used in design and management. It often uses contracted manufacturing and repair process capabilities, but is also driven by regulations and legislation.

The drawback of infrastructure's design service life, below T^D (see Fig.2.1) is considered a failure both by infrastructure beneficiaries and administrators and only in very few cases large efforts of manning and maintenance can restore it to designed service life.

For simplification, in Fig. 3.2 is made the assumption that optimal and minimum accepted performance levels are stationary most of infrastructure's lifespan. In practice one can rarely come across this type of behavior as user's higher expectations evolve most of them due to development of new infrastructures and facilities, new emerging technologies, new standards (see Fig. 3.3).

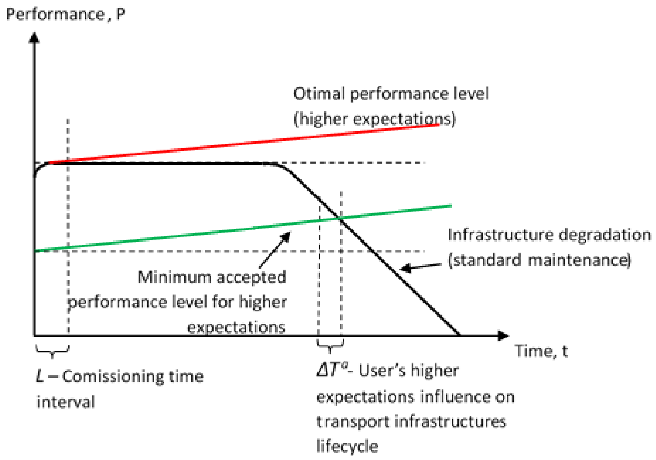

***Fig 3.2** Higher user's expectation effect on modification of infrastructure's lifecycle*

If we refer to equation $P(t)<P^T$, the infrastructure's performance threshold minimum level can be described as in equation 3.1:

$$P^F = P^F(E_k, t) \tag{3.1}$$

Where E_k represent exogenously and environment factors (new emerging technologies, economic and social environment, beneficiaries higher expectation, behavior changes) challenging infrastructure's performance level.

t – time.

User's higher expectation lids to a decrease in perceived performance level and finally to infrastructure obsolescence.

A good measure for obsolescence is the decrease in design service life. Obsolescence occurs when P^F, performance threshold minimum level, increases rapidly due to exogenously and environment factors and the real lifespan goes well beyond optimum expected lifespan, characterized by an expected performance level at t_0 as in equation 3.2:

$$E[P(t=t_0 / X_i, D_j)] < P^F(t=t_0 / E_K), \tag{3.2}$$

for $t_0 < T^D$

where t_0 is the starting moment from which infrastructure is considered obsolete.

The function $P^F(E_K, t)$ is known as „expectation function". The growth rate of this function of expectations can vary very rapidly, as shown in Figure 3. 3.

Standardization and regulatory actions are potential sources of both system functional (demand side) obsolescence and component (supply side) obsolescence. If transport infrastructure facilities are not compliant with a new standard, it can no longer be used or is subject to significant usage restrictions. Rules and mandates are regulatory instruments that impose new operational requirements or procedures. They may impose new functional requirements on infrastructure's features, but require new equipment and installations [12].

The infrastructure's obsolescence related with the change of regulations or standards can be represented in the form of a scale function (see Fig. 3.3), although these changes are often preceded by significant periods of time dedicated to public discussions and debates.

The overcoming of a new standard/given technology due to technical, legislative and/or marketing reasons typically leads to a decrease in value of the system which is not necessarily related to its past or current performance but can certainly influence its future life. Indeed, the availability on the market of improved components offers the enviable opportunity to plant managers of upgrading their system performance while rejuvenating the system itself [7].

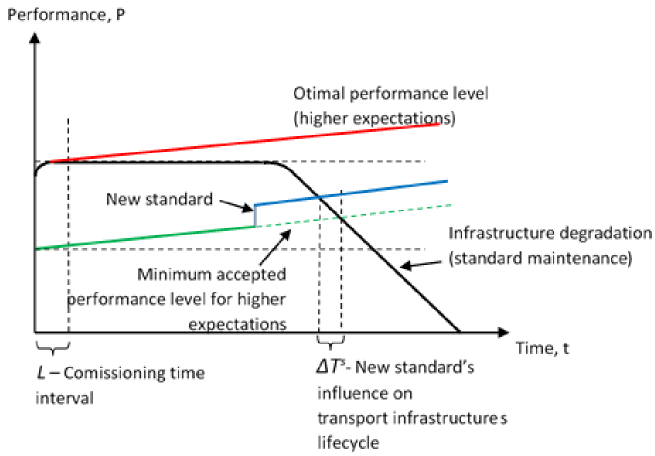

***Fig.3.3** Change of regulations or standards effect on modification of infrastructure's lifecycle*

However, obsolete infrastructures can still be used, but if they are not replaced or upgraded, they create a wide variety of inconveniences for users, managers and residents (e.g., loss of capacity, environmental degradation, very high operating and maintenance costs).

Other factors that can be included in the E_K vector of exogenous or environmental factors are: the level of economic development and industrialization, the location of the infrastructure, the availability of alternative infrastructures.

4. Conclusions

The evaluation of the transport infrastructures efficiency must be assessed at the global social level and reflect the interests of all those involved and affected by the transport process on the infrastructure: the interests of users, managers, operators and residents who feel the positive and negative external effects of system activity (see Tab 4.1). All these effects can be quantified by a generalized cost function that combines the monetary and non-monetary costs at global society level, costs are related to transport, but involves a lot of parameters that are difficult to estimate and which, in most cases, require simplifications [9].

For this reason, for synthetic assessments regarding the efficiency of transport infrastructures, no explicit calculations can be made, but instead, the use of quantitative and qualitative criteria and indicators is preferred. Based on this indicators, the achievements are compared with the previous ones, with those of similar systems, in order to guide the decisions regarding the technical, technological and organizational improvement. The complexity of some aspects regarding calculation of the transport efficiency led to the necessity of go into detail and structure a set of indicators of great variety some of them with a pronounced contradictory character.

***Table 4.1:** Outputs of transport infrastructure performance assessment*

Actors involved and affected by transport infrastructure performance assessment	Outputs of transport infrastructure performance assessment	
Users	Improved speed, availability and reliability of trips	Enhanced safety due to efficient maintenance and asset health monitoring.

Transport infrastructure personnel maintenance	Enables planned maintenance as opposed to emergency intervention.	Provides the capability to analyze any breakdowns from trend measurements, thus providing valuable information about the nature of the breakdown and facilitating swifter breakdown resolution.
Transport infrastructure managers	Greater availability of assets including rolling stock as a result of fewer breakdowns and swifter breakdown resolution.	Enables monitoring of infrastructure equipment and components, making it possible to identify operational deviations in time.
Transport infrastructure companies	Provides improved insight and elevates the entire maintenance process. Far fewer unscheduled repairs are needed and condition linked maintenance generates cost savings and efficiency gains.	Companies can keep their operations running longer and more frequently. This helps keep operational costs under control.

The choice of the most appropriate reliability indicator must take into account considerations regarding simplicity, statistical stability and its importance in defining the functionality of the system. It must also be based on the types of technological disturbances and the correct assessment of their consequences. The calculation of reliability indicators for transport infrastructures does not present major methodological difficulties.

The choice of the efficiency criterion for transport infrastructure appraisal is a delicate issue and is equivalent to the correct formulation of the objectives and the vector of possible solutions [13]. The designers and managers of the transport infrastructures try, most of the times, to ensure those properties of the infrastructure for which the level of efficiency is the appropriate one. Excess supply over demand is generally accepted as a possible sideline of satisfaction for the expected future growth, as a safety factor for possible nonlinearities of demand or only as a higher level of quality offered beyond the functional minimum imposed by standards [14].

The operation of transport infrastructures is affected by random factors of internal and external nature, which can cause changes in the performance of a facility, of the entire infrastructure or even for the entire transport system as a whole.

That is why average values of the efficacy criterion must be used.

Further, if one tries to spread the analysis from efficiency to effectiveness, one will find that involved actors: transport infrastructure managers, operators, beneficiaries and infrastructure's neighbors often pursue conflicting interests and this makes it necessary to specify some elements and requirements that are restrictive. The strategy is to ensure a "satisfactory" level rather than an optimum one. For example, the "capacity of a section of road artery" can only be a criterion of effectiveness accompanied by clarifications on the duration of the trip, the taxes collected, etc. "Travel time" or "journey time" (or the corresponding average speeds in a given relationship) could be relevant efficiency criteria for infrastructure users / beneficiaries.

In the best practice studies of restructuring / development of a transport infrastructure, the efficiency of various possible technical solutions can be estimated as follows: only equivalent solutions are retained for ranking in terms of meeting quantitative (e.g. capacity) and qualitative requirements (e.g. travel / transport duration), facilities for users, comfort, storage of goods). In this situation, the selection among given solutions, a choice can be made by comparing the equivalent expenses to ensure the desired level of imposed performance measures (e.g. capacity, reliability, safety).

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4. References

[1] Jean-Paul Rodrigue *The Geography of Transport Systems,* New York: Routledge, 456 pages, (2020)

[2] Lemer, A.C.*Performance of systems of constructed facilities,* PHD thesis, Massachusetts Inst. of Technology, Cambridge, (1971)

[3] Lemer, A.C. *Obsolence and Design Service life,* Journal or Infrastructure Systems, p. 153 – 156, (1996)

[4] Lemer, A.C.*Measuring performance of airport passenger terminals,* Transportation research Part A, 26A, p. 37-45, (1992)

[5] Bell, M.G.H., Iida, Y. *Transportation Network Analysis,* Chichester, John Wiley & Sons (1997)

[6] Taylor, M., and D'Este, G Transport Network Vulnerability: a Method for Diagnosis of Critical Locations in Transport Infrastructure Systems in *Critical Infrastructure: Reliability and Vulnerability*, Springer Verlang (2007)

[7] Brown M, Proschan F. Imperfect repair. J Appl Probab 1983;20:851–9.

[8] Lim TJ. Estimating system reliability with fully masked data under Brown–Proschan imperfect repair model. Reliab Engng System Safety 1998;59:277–89.

[9] Sherif YS, Smith ML. Optimal maintenance models for systems subject to failure—a review. Nav Res Log Quart 28:47–74 (1981)

[10] E. Borgonovo et al. A Monte Carlo methodological approach to plant availability modelling with maintenance, aging and obsolescence, Reliability Engineering and System Safety 67, 61–73, (2000)

[11] Song JS, Zipkin PH. Managing inventory with the prospect of obsolescence. Oper Res;44:215–24, (1993)

[12] Pecht, M., Solomon, R., Sandborn, P., Das, D., and Wilkinson, C., Life-Cycle Forecasting, Mitigation Assessment and Obsolescence Strategies, CALCE EPSC Press, College Park, Maryland, 2002

[13] Raicu, Ş., *Transport Systems,* Editura AGIR, Bucuresti, (2007)

[14] Fortuin, L. *Performance indicators — Why, where and how?* European Journal of Operational Research Volume 34, Issue 1, (1988)